Exhibit A

US005819292A

United States Patent [19]

Hitz et al.

[11] **Patent Number: 5,819,292**

[45] **Date of Patent: Oct. 6, 1998**

[54] **METHOD FOR MAINTAINING CONSISTENT STATES OF A FILE SYSTEM AND FOR CREATING USER-ACCESSIBLE READ-ONLY COPIES OF A FILE SYSTEM**

[75] Inventors: **David Hitz**, Sunnyvale; **Michael Malcolm**, Los Altos; **James Lau**, Cupertino; **Byron Rakitzis**, Mountain View, all of Calif.

[73] Assignee: **Network Appliance, Inc.**, Santa Clara, Calif.

[21] Appl. No.: **454,921**

[22] Filed: **May 31, 1995**

Related U.S. Application Data

[63] Continuation of Ser. No. 71,643, Jun. 3, 1993, abandoned.

[51] **Int. Cl.**[6] **G06F 17/30**

[52] **U.S. Cl.** **707/203**; 707/205

[58] **Field of Search** 395/621, 619

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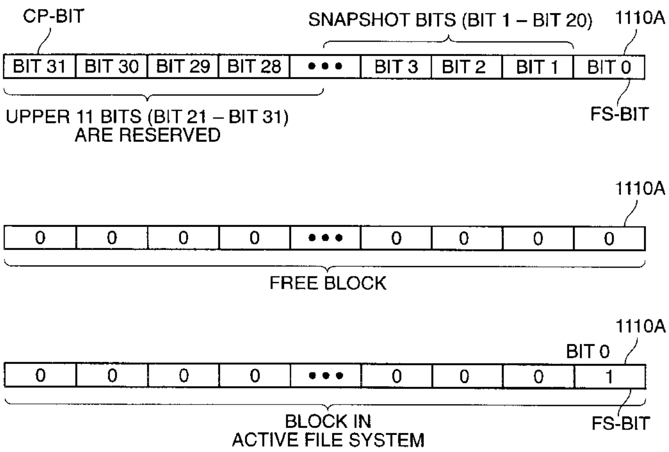
Attorney, Agent, or Firm—D'Alessandro & Ritchie

[57] **ABSTRACT**

A method is disclosed for maintaining consistent states of a file system. The file system progresses from one self-consistent state to another self-consistent state. The set of self-consistent blocks on disk that is rooted by a root inode is referred to as a consistency point. The root inode is stored in a file system information structure. To implement consistency points, new data is written to unallocated blocks on disk. A new consistency point occurs when the file system information structure is updated by writing a new root inode into it. Thus, as long as the root inode is not updated, the state of the file system represented on disk does not change. The method also creates snapshots that are user-accessible read-only copies of the file system. A snapshot uses no disk space when it is initially created. It is designed so that many different snapshots can be created for the same file system. Unlike prior art file systems that create a clone by duplicating an entire inode file and all indirect blocks, the method of the present invention duplicates only the inode that describes the inode file. A multi-bit free-block map file is used to prevent data referenced by snapshots from being overwritten on disk.

20 Claims, 39 Drawing Sheets



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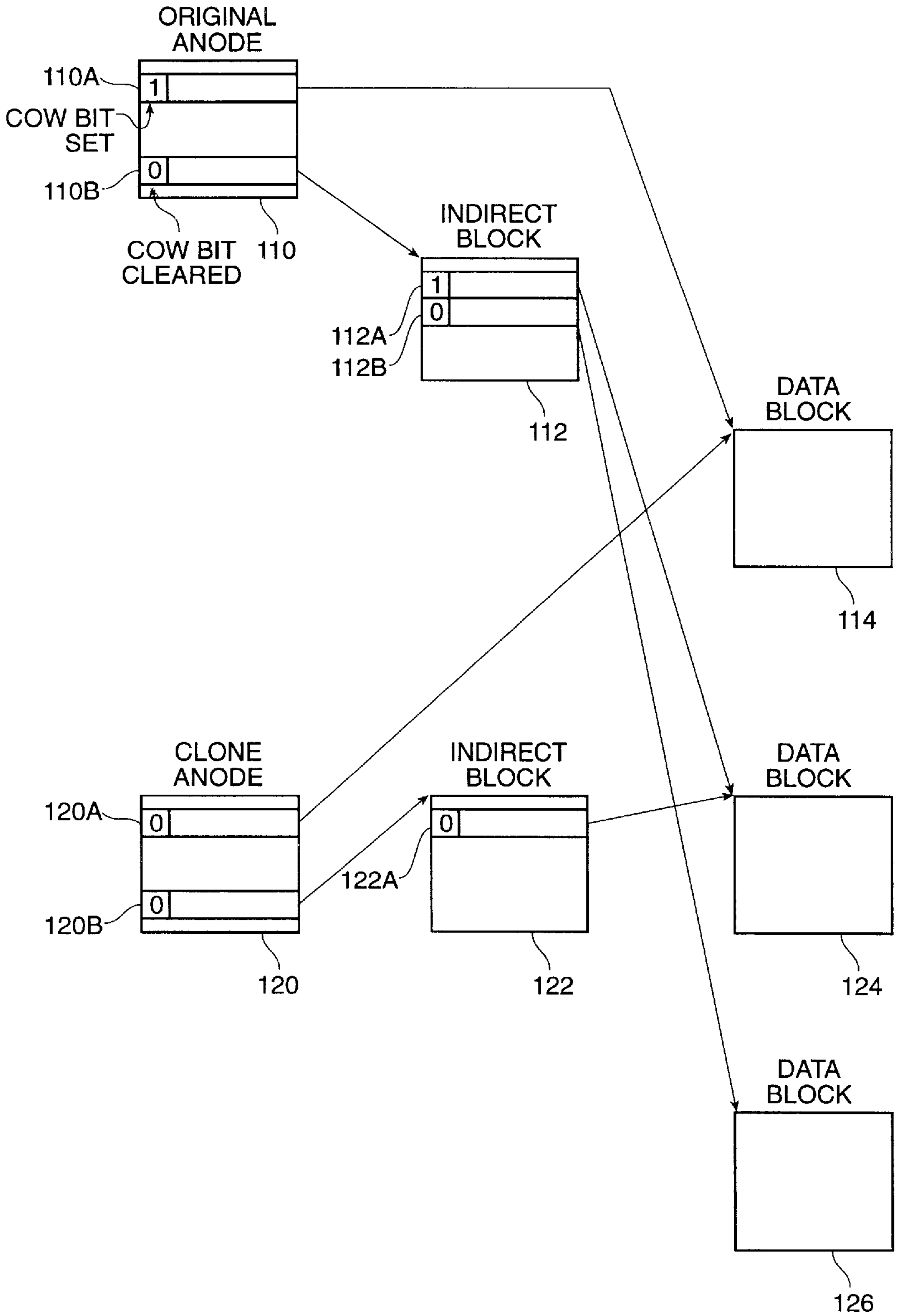
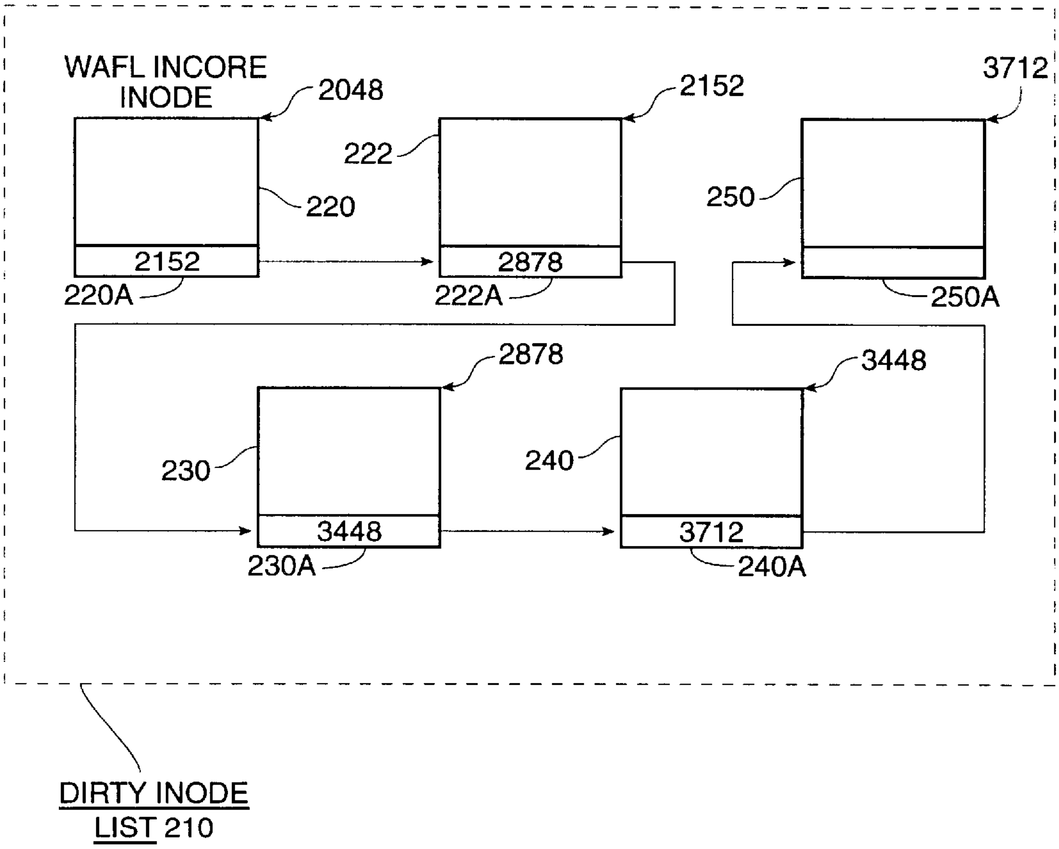
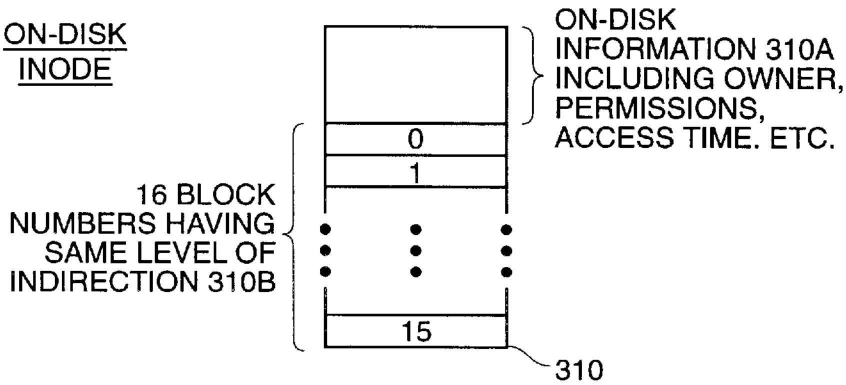


FIG. 1
PRIOR ART



WAFL INCORE INODE
2048
2152
3712
222
220
250
2152
2878
220A
222A
250A
2878
3448
230
240
3448
3712
230A
240A
DIRTY INODE LIST 210

FIG. 2



ON-DISK INODE
ON-DISK INFORMATION 310A INCLUDING OWNER, PERMISSIONS, ACCESS TIME. ETC.
0
1
16 BLOCK NUMBERS HAVING SAME LEVEL OF INDIRECTION 310B
15
310

FIG. 3

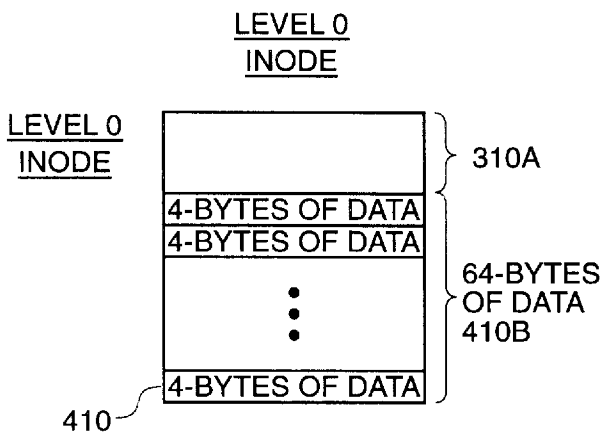

LEVEL 0
INODE
LEVEL 0
INODE
310A
4-BYTES OF DATA
4-BYTES OF DATA
4-BYTES OF DATA
64-BYTES
OF DATA
410B
410

FIG. 4A

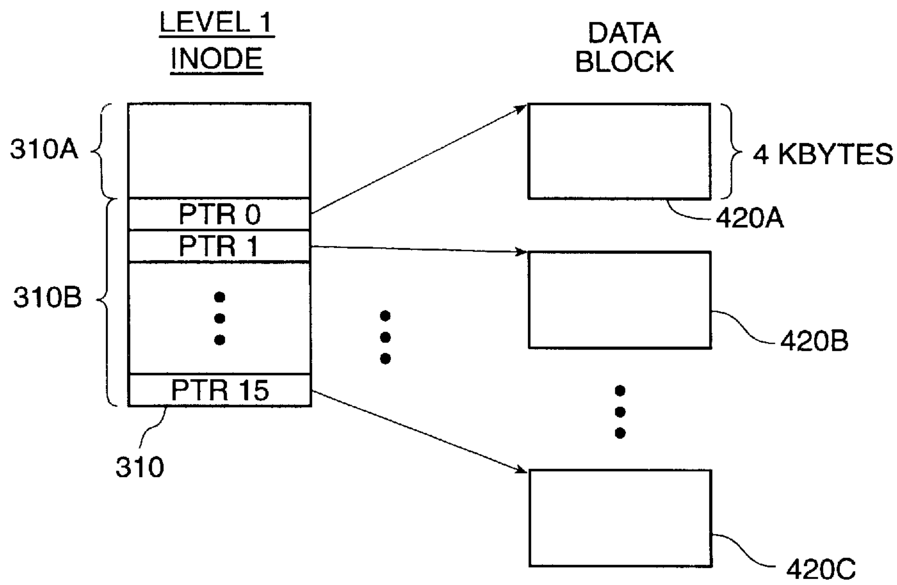

LEVEL 1
INODE
DATA
BLOCK
310A
PTR 0
PTR 1
310B
PTR 15
310
4 KBYTES
420A
420B
420C

FIG. 4B

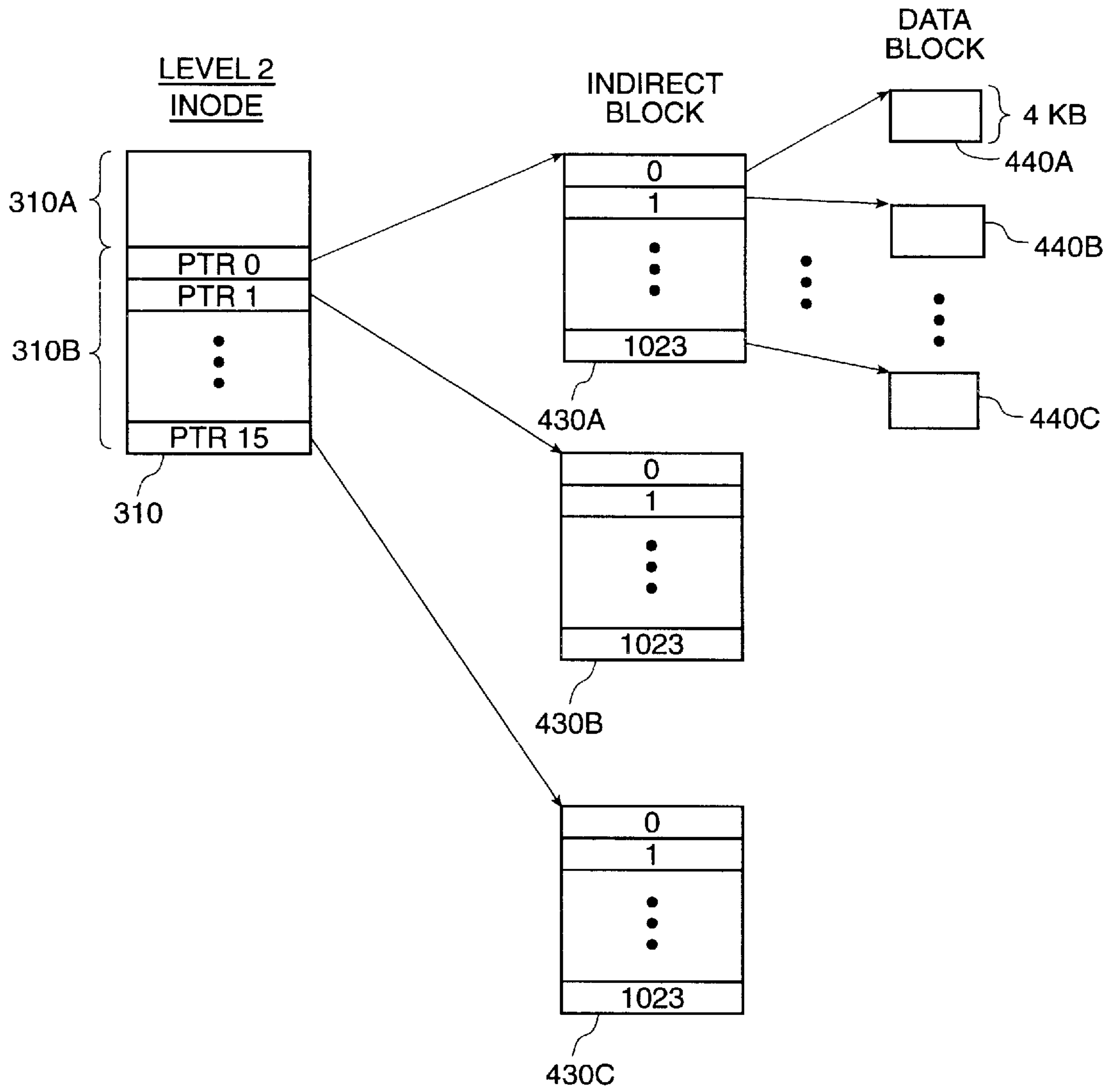
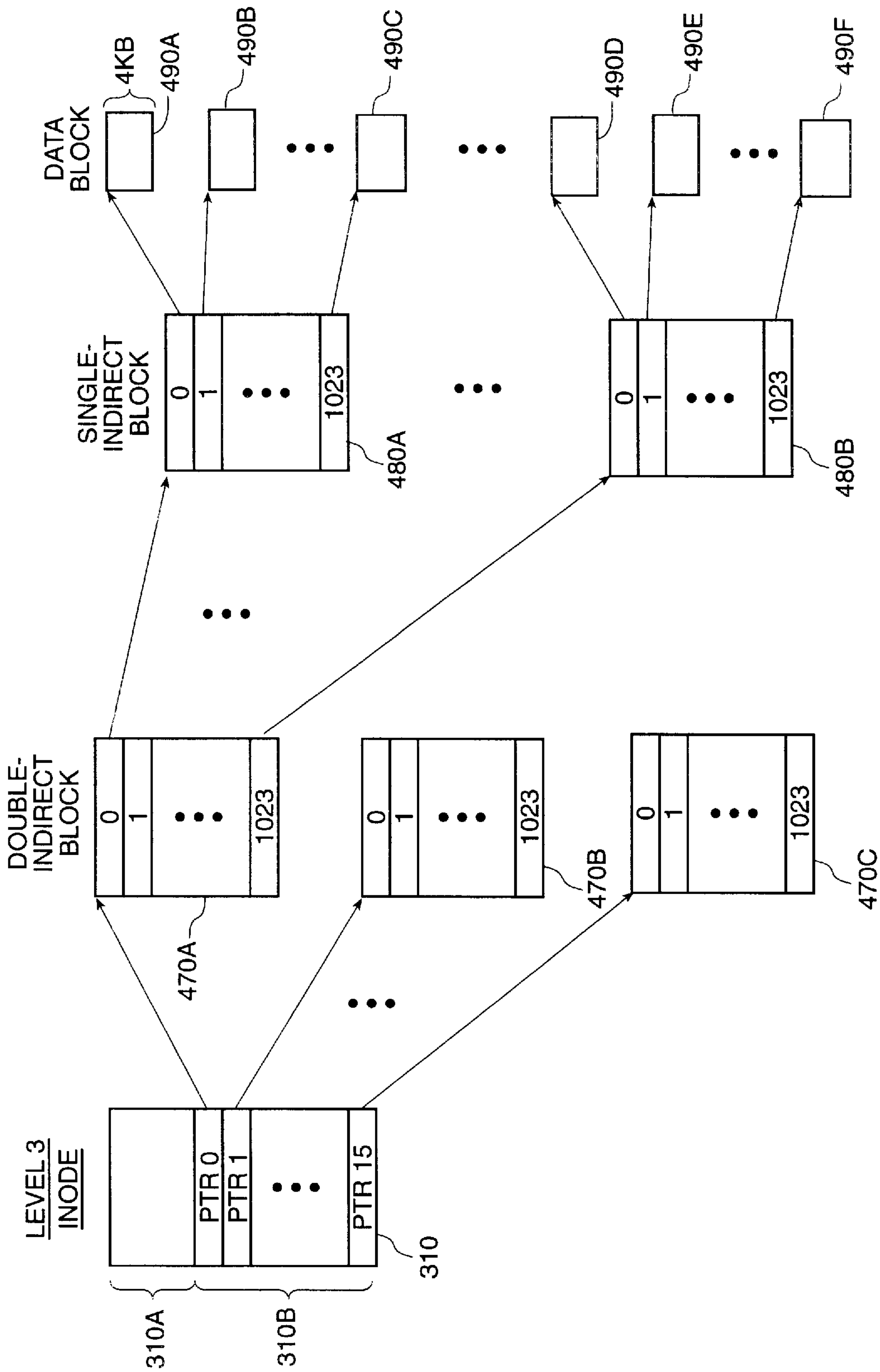

LEVEL 2
INODE
310A
310B
PTR 0
PTR 1
PTR 15
310
INDIRECT
BLOCK
0
1
1023
430A
430B
430C
DATA
BLOCK
4 KB
440A
440B
440C

FIG. 4C



LEVEL 3 INODE
PTR 0
PTR 1
PTR 15
310
310A
310B
DOUBLE-INDIRECT BLOCK
0
1
1023
470A
470B
470C
SINGLE-INDIRECT BLOCK
480A
480B
DATA BLOCK
4KB
490A
490B
490C
490D
490E
490F

FIG. 4D

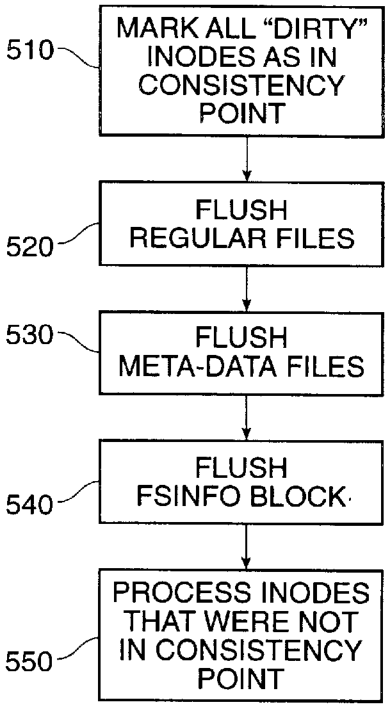

510
MARK ALL "DIRTY" INODES AS IN CONSISTENCY POINT
520
FLUSH REGULAR FILES
530
FLUSH META-DATA FILES
540
FLUSH FSINFO BLOCK
550
PROCESS INODES THAT WERE NOT IN CONSISTENCY POINT

FIG. 5

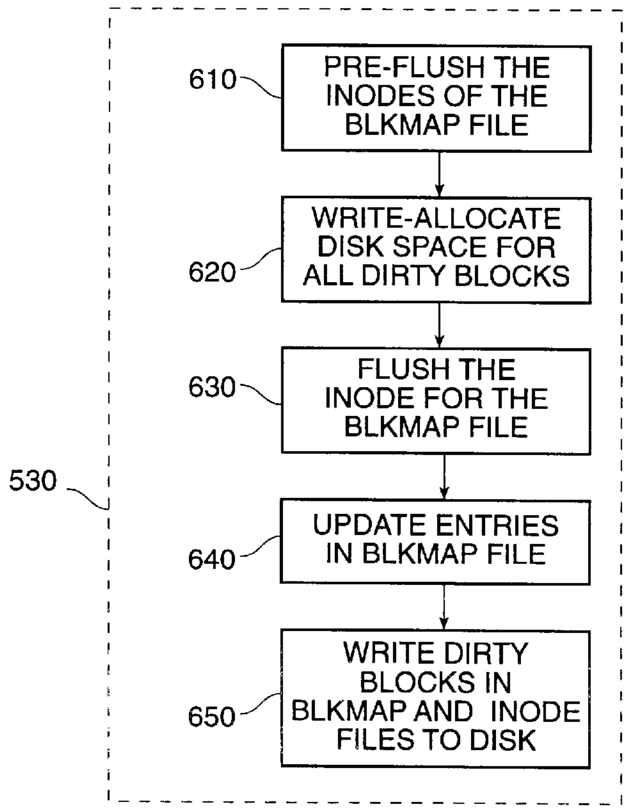

530
610
PRE-FLUSH THE INODES OF THE BLKMAP FILE
620
WRITE-ALLOCATE DISK SPACE FOR ALL DIRTY BLOCKS
630
FLUSH THE INODE FOR THE BLKMAP FILE
640
UPDATE ENTRIES IN BLKMAP FILE
650
WRITE DIRTY BLOCKS IN BLKMAP AND INODE FILES TO DISK

FIG. 6

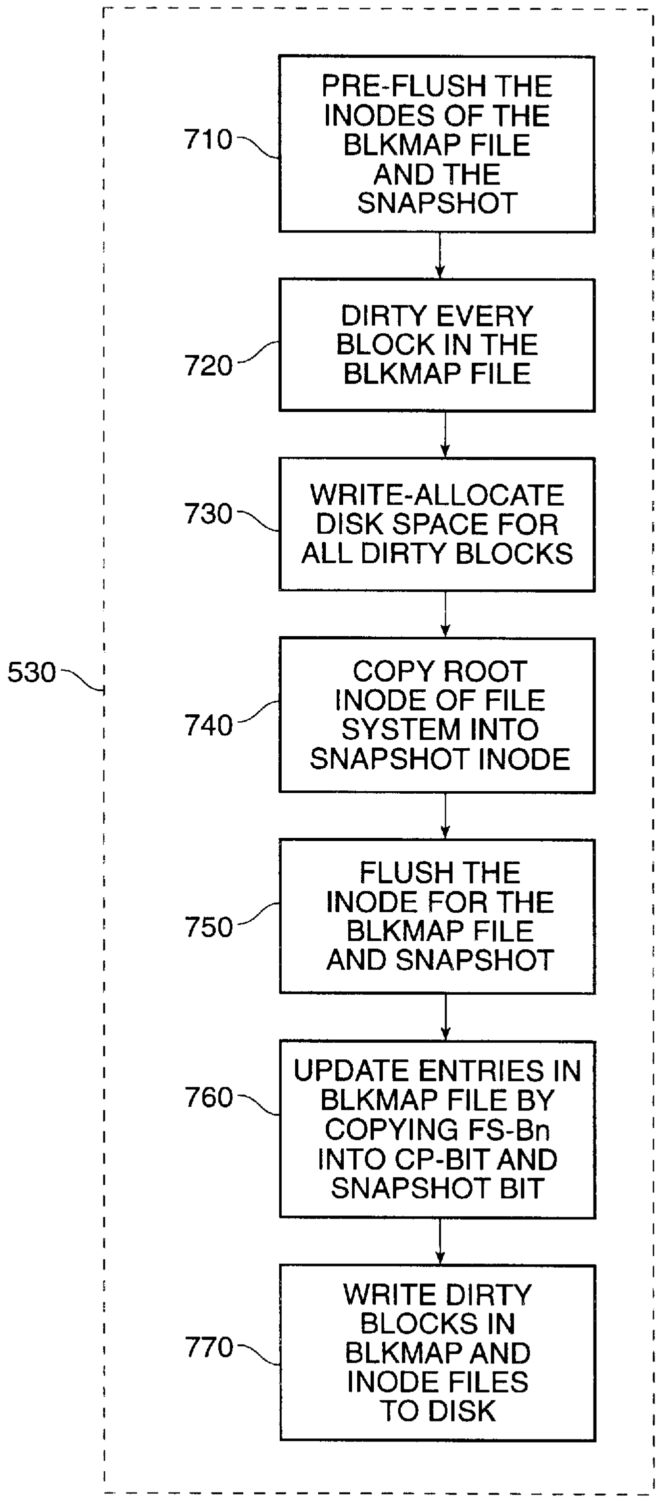

530
710
PRE-FLUSH THE INODES OF THE BLKMAP FILE AND THE SNAPSHOT
720
DIRTY EVERY BLOCK IN THE BLKMAP FILE
730
WRITE-ALLOCATE DISK SPACE FOR ALL DIRTY BLOCKS
740
COPY ROOT INODE OF FILE SYSTEM INTO SNAPSHOT INODE
750
FLUSH THE INODE FOR THE BLKMAP FILE AND SNAPSHOT
760
UPDATE ENTRIES IN BLKMAP FILE BY COPYING FS-Bn INTO CP-BIT AND SNAPSHOT BIT
770
WRITE DIRTY BLOCKS IN BLKMAP AND INODE FILES TO DISK

FIG. 7

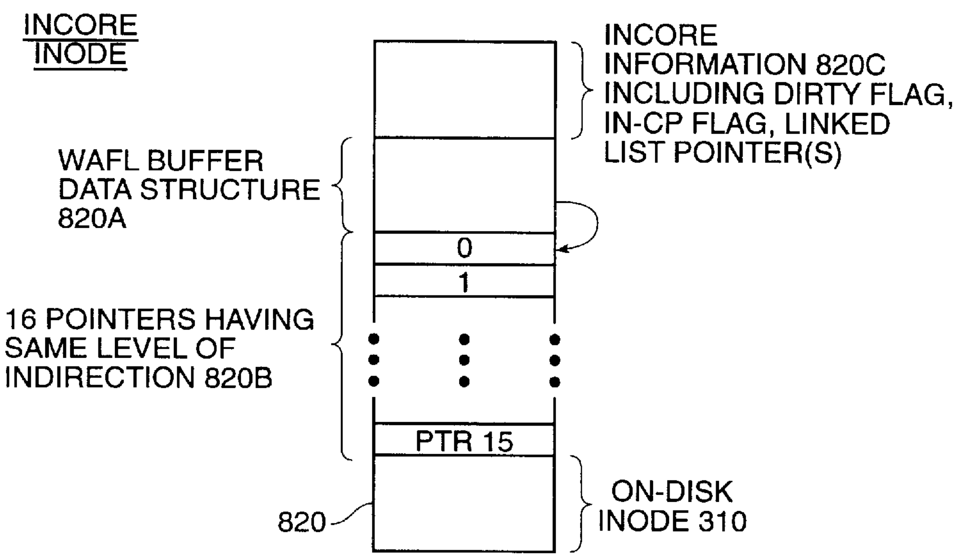

INCORE INODE
INCORE INFORMATION 820C INCLUDING DIRTY FLAG, IN-CP FLAG, LINKED LIST POINTER(S)
WAFL BUFFER DATA STRUCTURE 820A
0
1
16 POINTERS HAVING SAME LEVEL OF INDIRECTION 820B
PTR 15
ON-DISK INODE 310
820

FIG.8

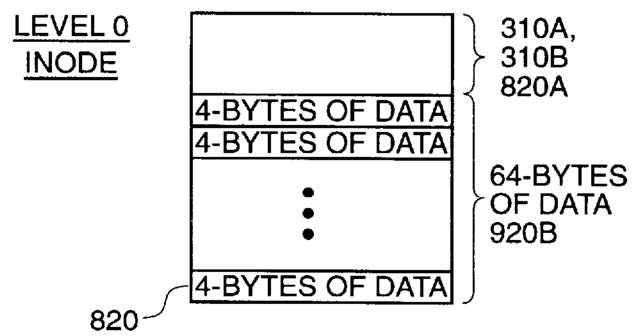

LEVEL 0
INODE
310A,
310B
820A
4-BYTES OF DATA
4-BYTES OF DATA
64-BYTES
OF DATA
920B
4-BYTES OF DATA
820

FIG. 9A

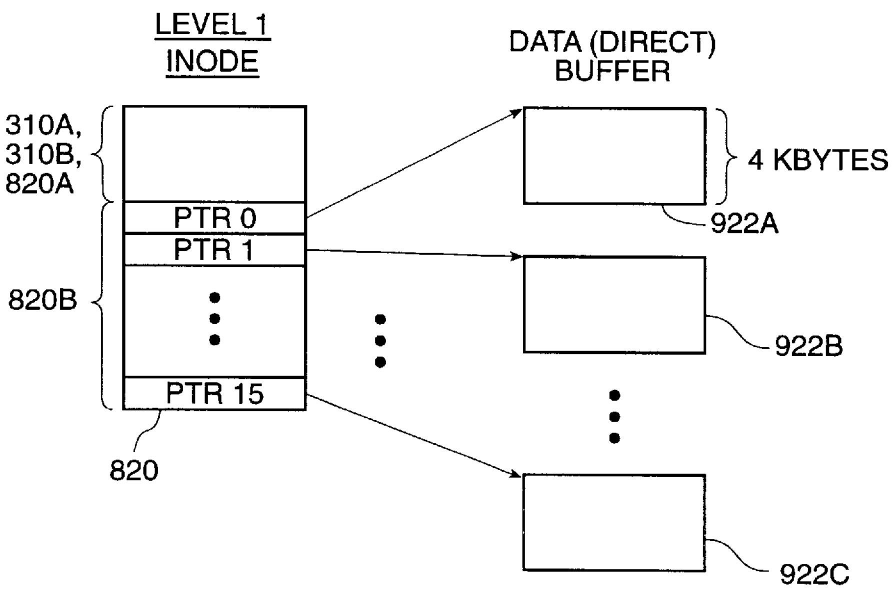
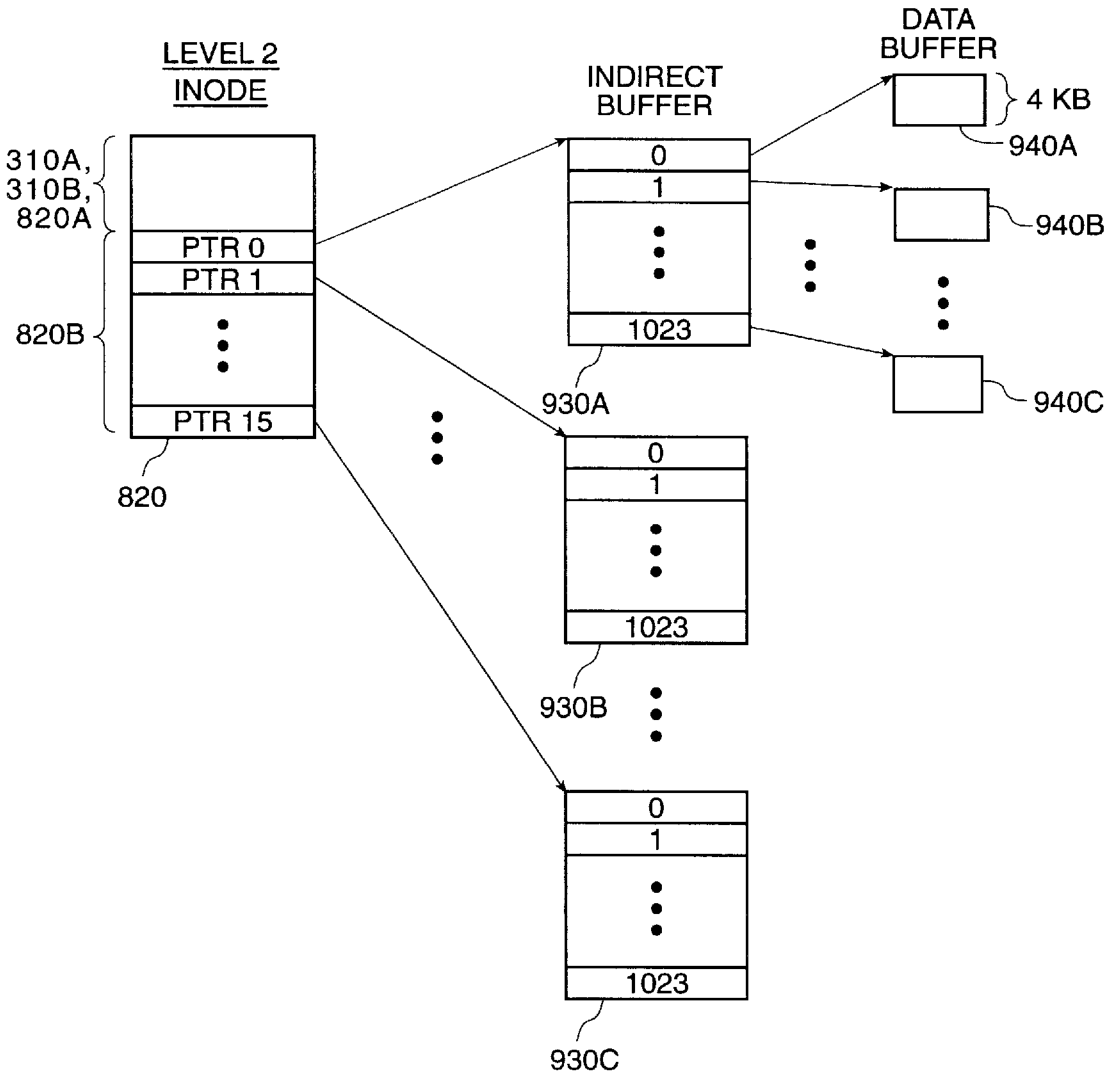

LEVEL 1
INODE
DATA (DIRECT)
BUFFER
310A,
310B,
820A
4 KBYTES
PTR 0
PTR 1
922A
820B
922B
PTR 15
820
922C

FIG. 9B



LEVEL 2
INODE
310A,
310B,
820A
PTR 0
PTR 1
820B
PTR 15
820
INDIRECT
BUFFER
0
1
1023
930A
930B
930C
DATA
BUFFER
4 KB
940A
940B
940C

FIG. 9C

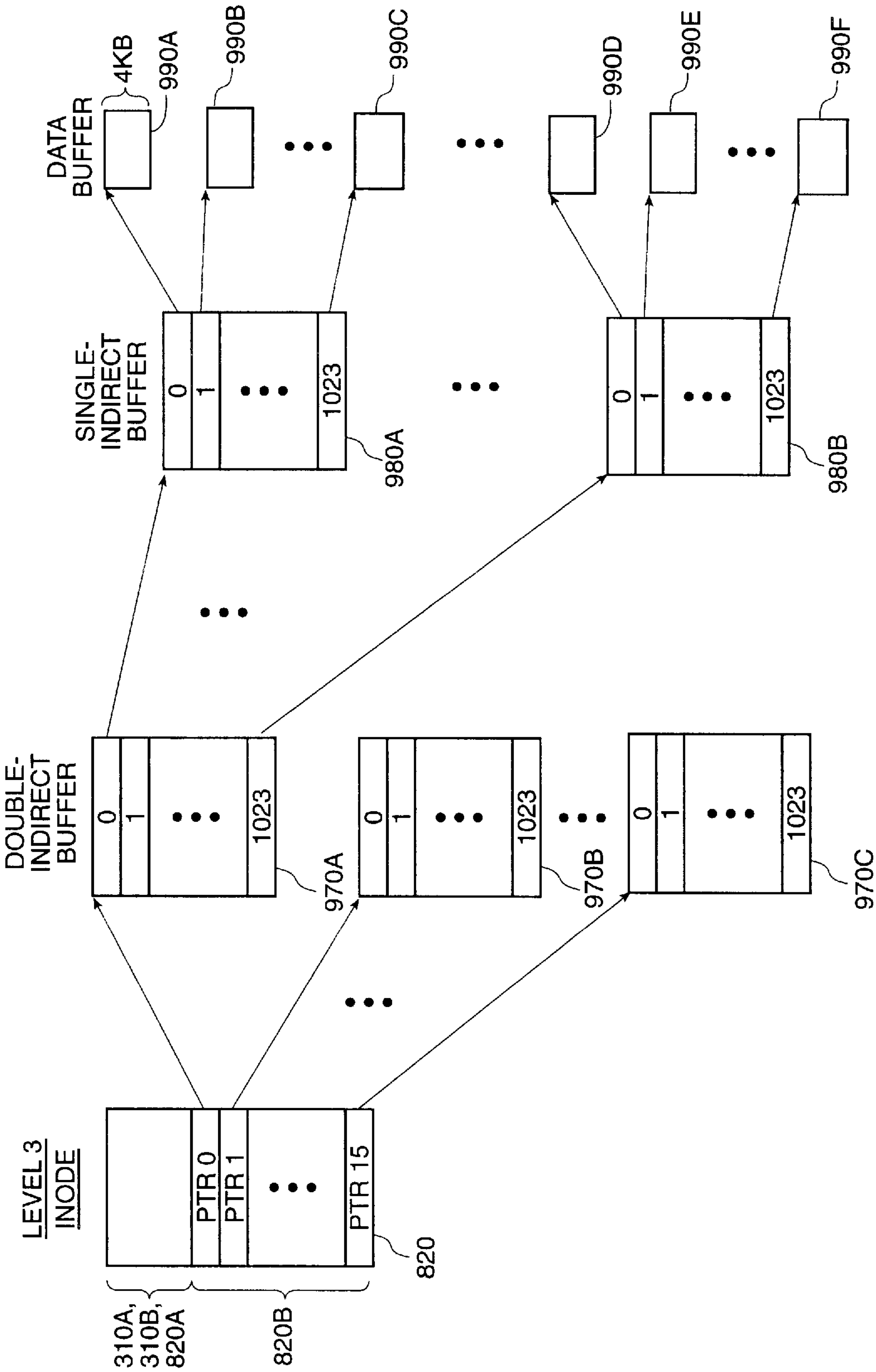
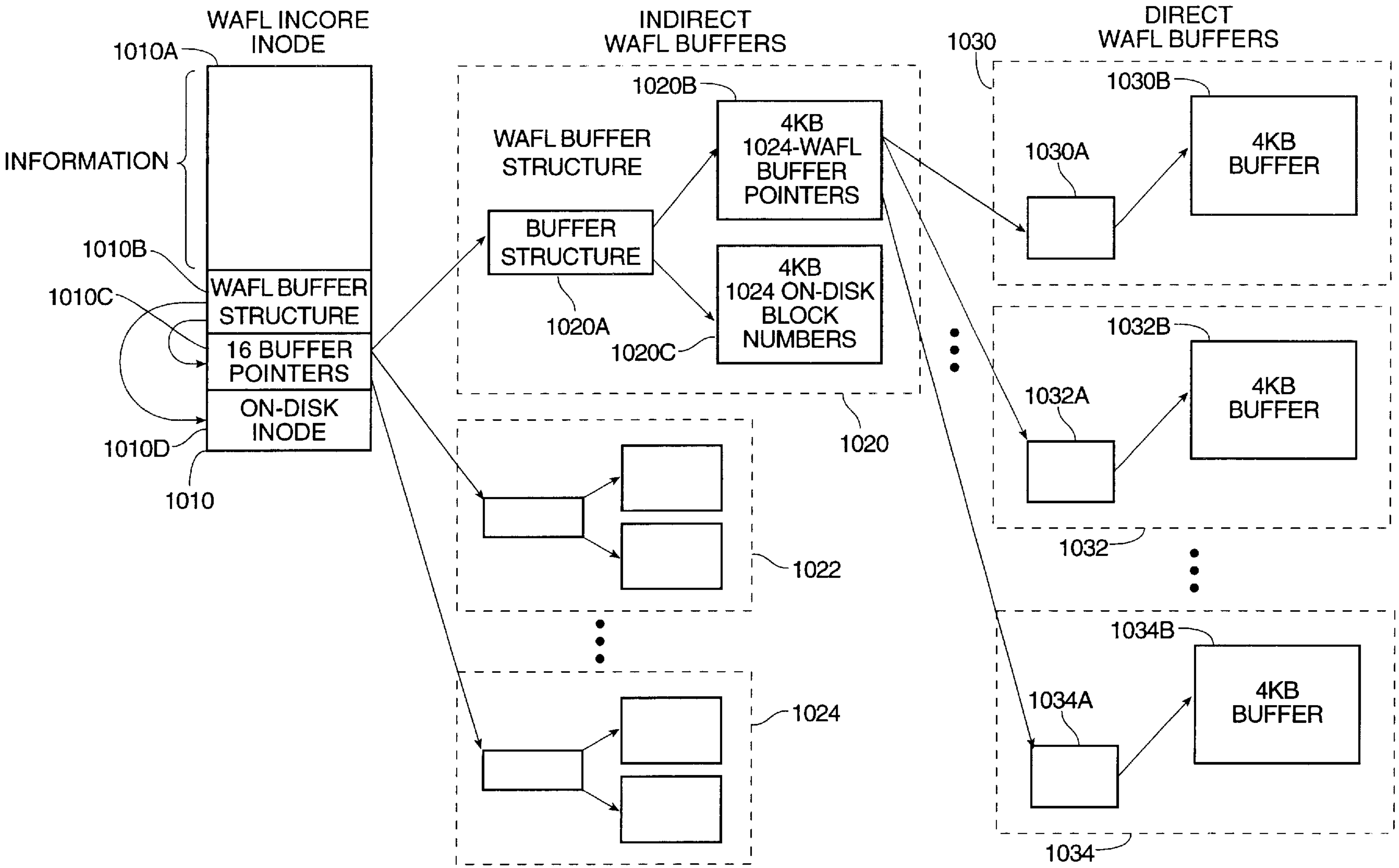

LEVEL 3
INODE
PTR 0
PTR 1
PTR 15
820
310A,
310B,
820A
820B
DOUBLE-
INDIRECT
BUFFER
0
1
1023
970A
970B
970C
SINGLE-
INDIRECT
BUFFER
980A
980B
DATA
BUFFER
4KB
990A
990B
990C
990D
990E
990F

FIG. 9D



WAFL INCORE INODE
1010A
INFORMATION
1010B
WAFL BUFFER STRUCTURE
1010C
16 BUFFER POINTERS
ON-DISK INODE
1010D
1010
INDIRECT WAFL BUFFERS
1020B
WAFL BUFFER STRUCTURE
BUFFER STRUCTURE
4KB 1024-WAFL BUFFER POINTERS
4KB 1024 ON-DISK BLOCK NUMBERS
1020A
1020C
1020
1022
1024
DIRECT WAFL BUFFERS
1030
1030B
1030A
4KB BUFFER
1032B
1032A
4KB BUFFER
1032
1034B
1034A
4KB BUFFER
1034

FIG. 10

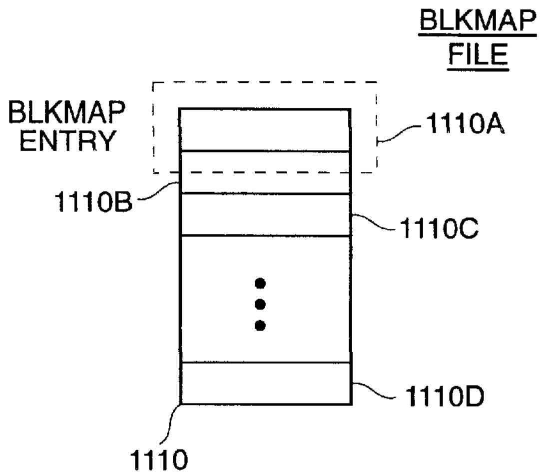


FIG. 11A

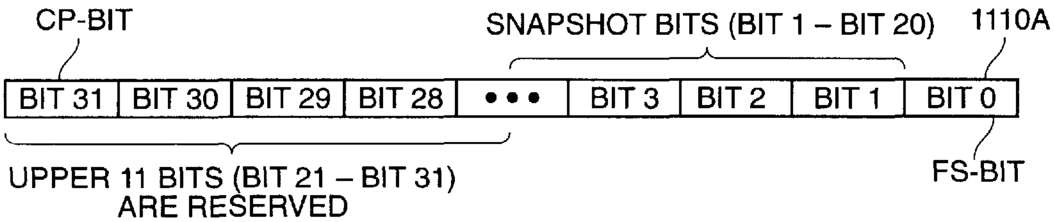


FIG. 11B

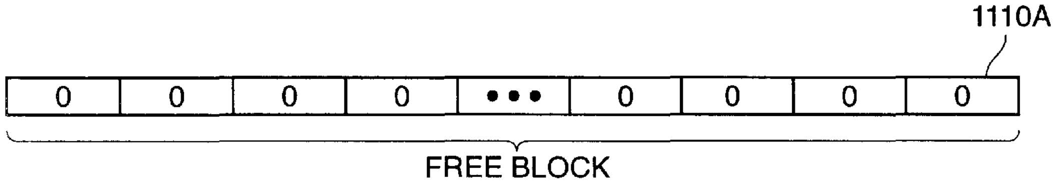


FIG. 11C

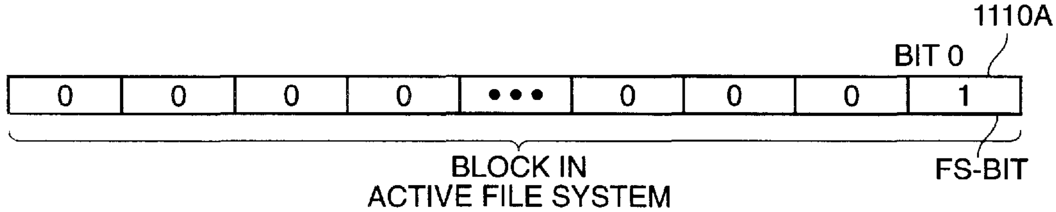


FIG. 11D

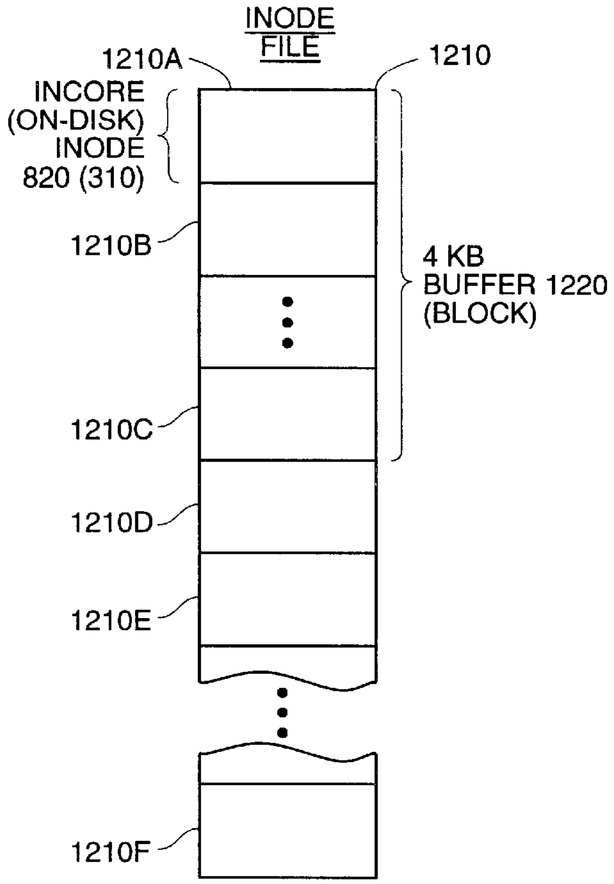

INODE FILE
1210A
1210
INCORE (ON-DISK) INODE 820 (310)
1210B
4 KB BUFFER 1220 (BLOCK)
1210C
1210D
1210E
1210F

FIG. 12

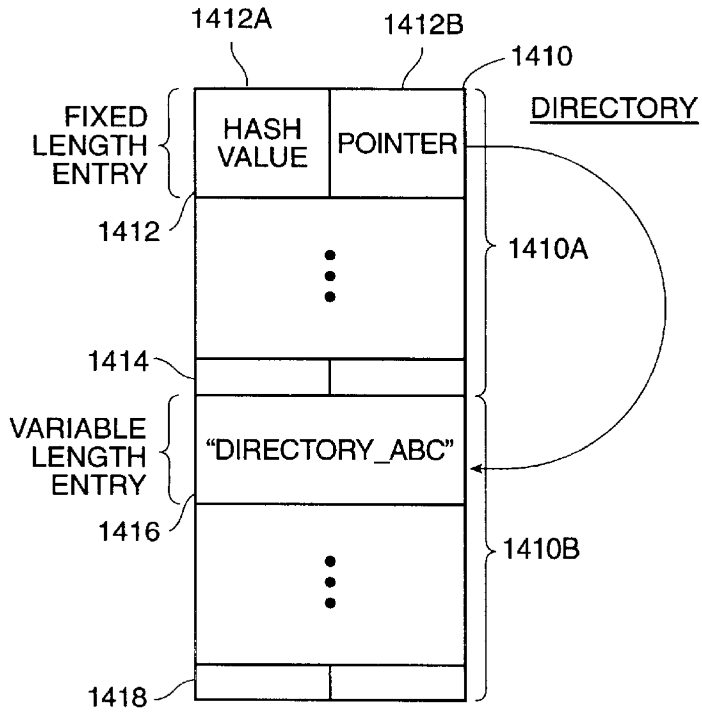

1412A
1412B
1410
DIRECTORY
FIXED LENGTH ENTRY
HASH VALUE
POINTER
1412
1410A
1414
VARIABLE LENGTH ENTRY
"DIRECTORY_ABC"
1416
1410B
1418

FIG. 14

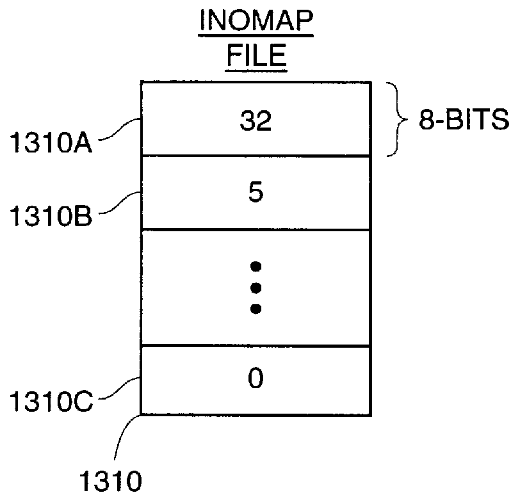


FIG. 13A

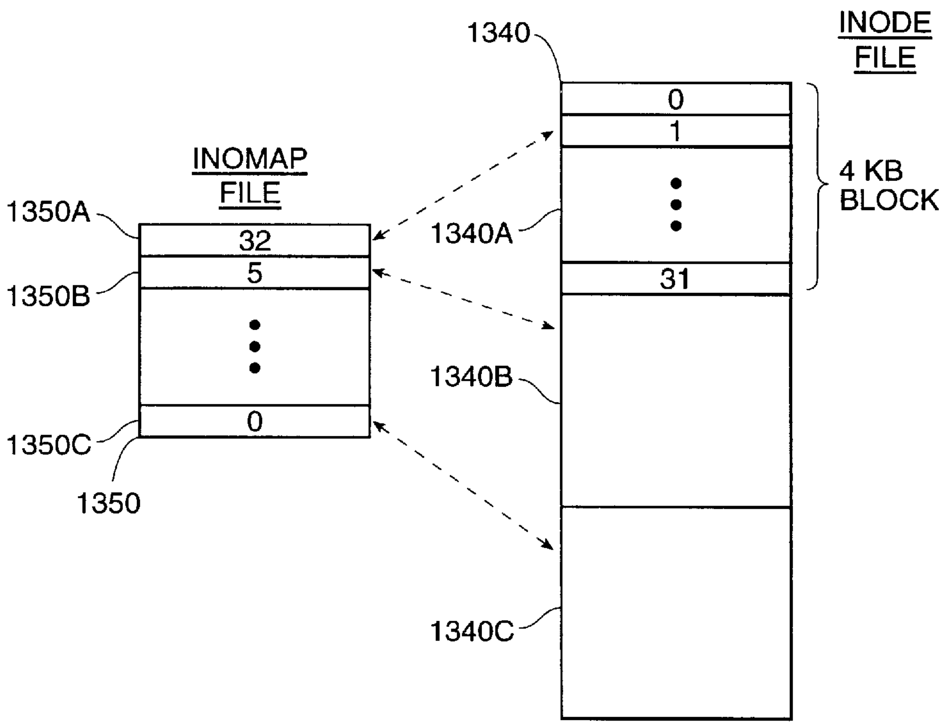


FIG. 13B

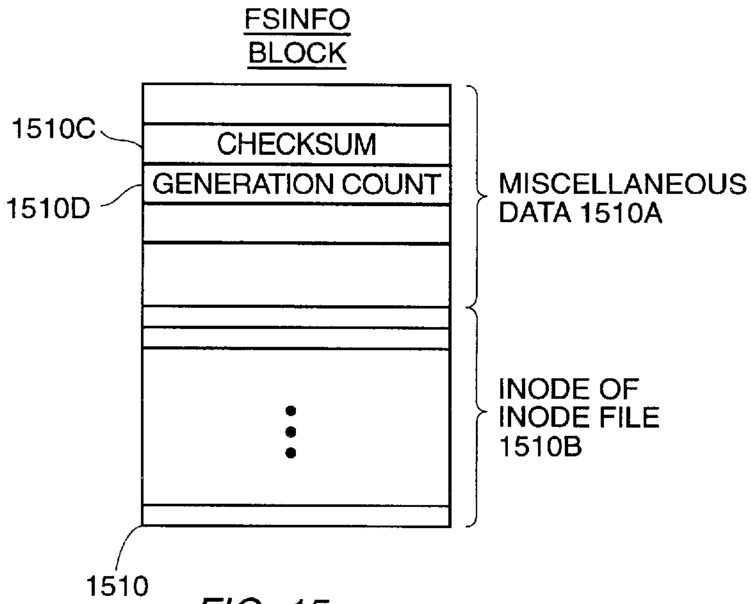


FIG. 15

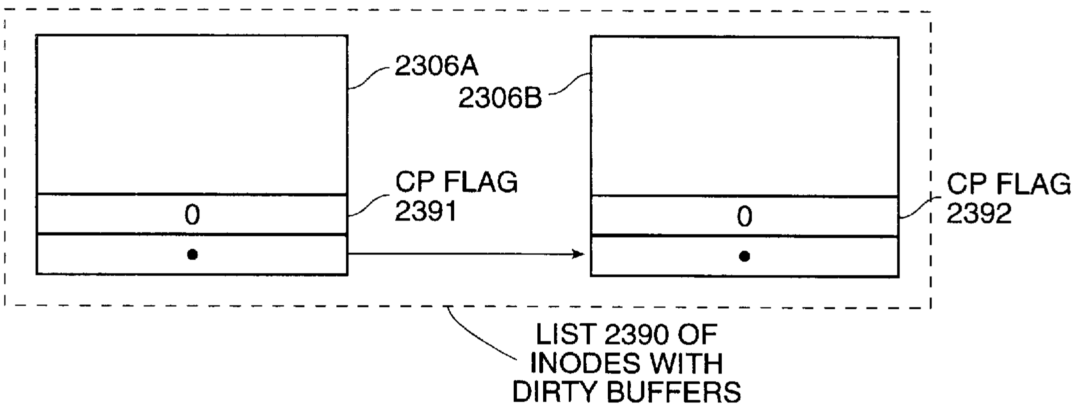


FIG. 17A

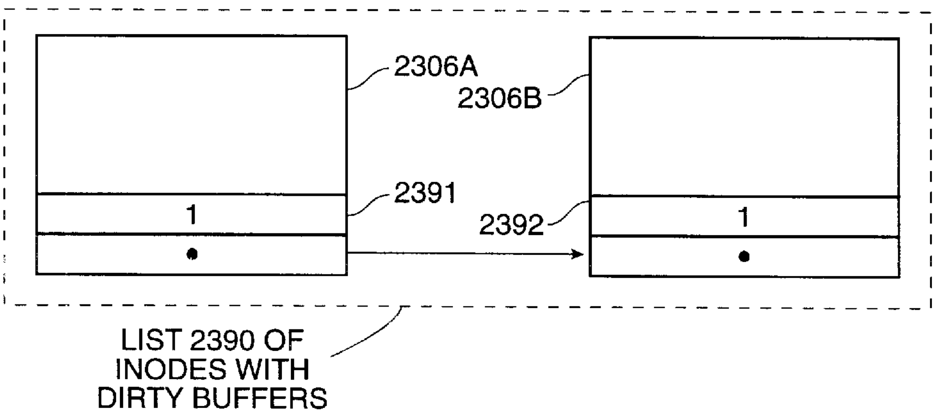
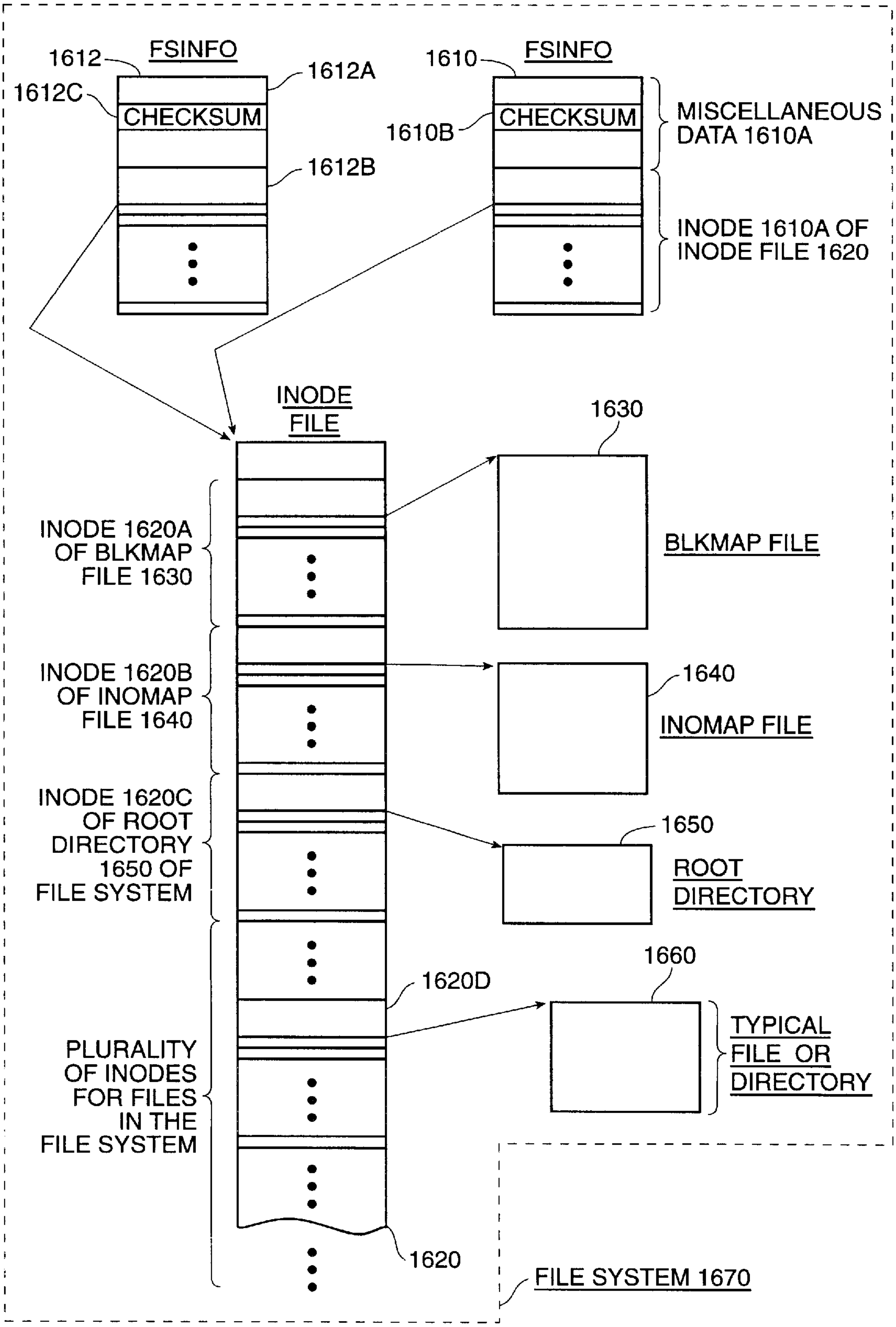
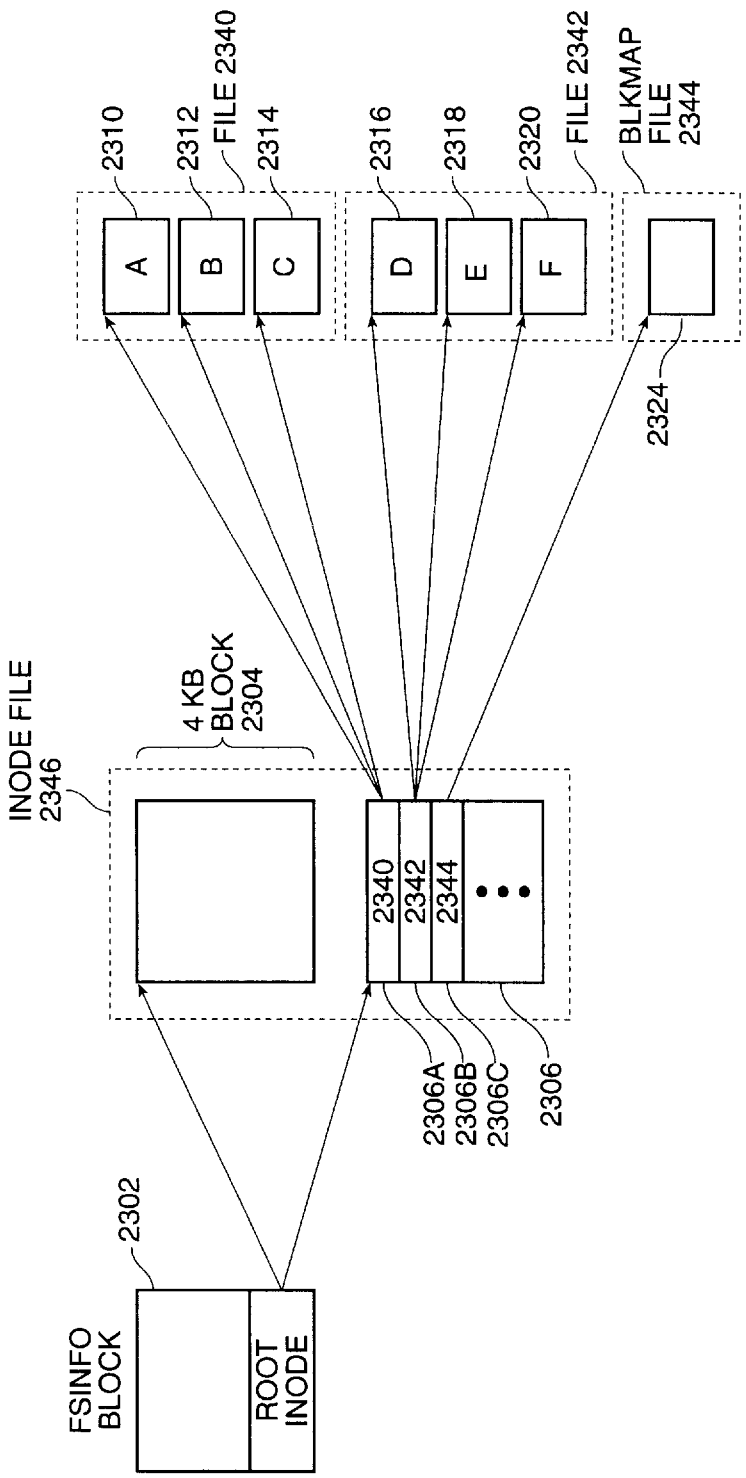


FIG. 17I



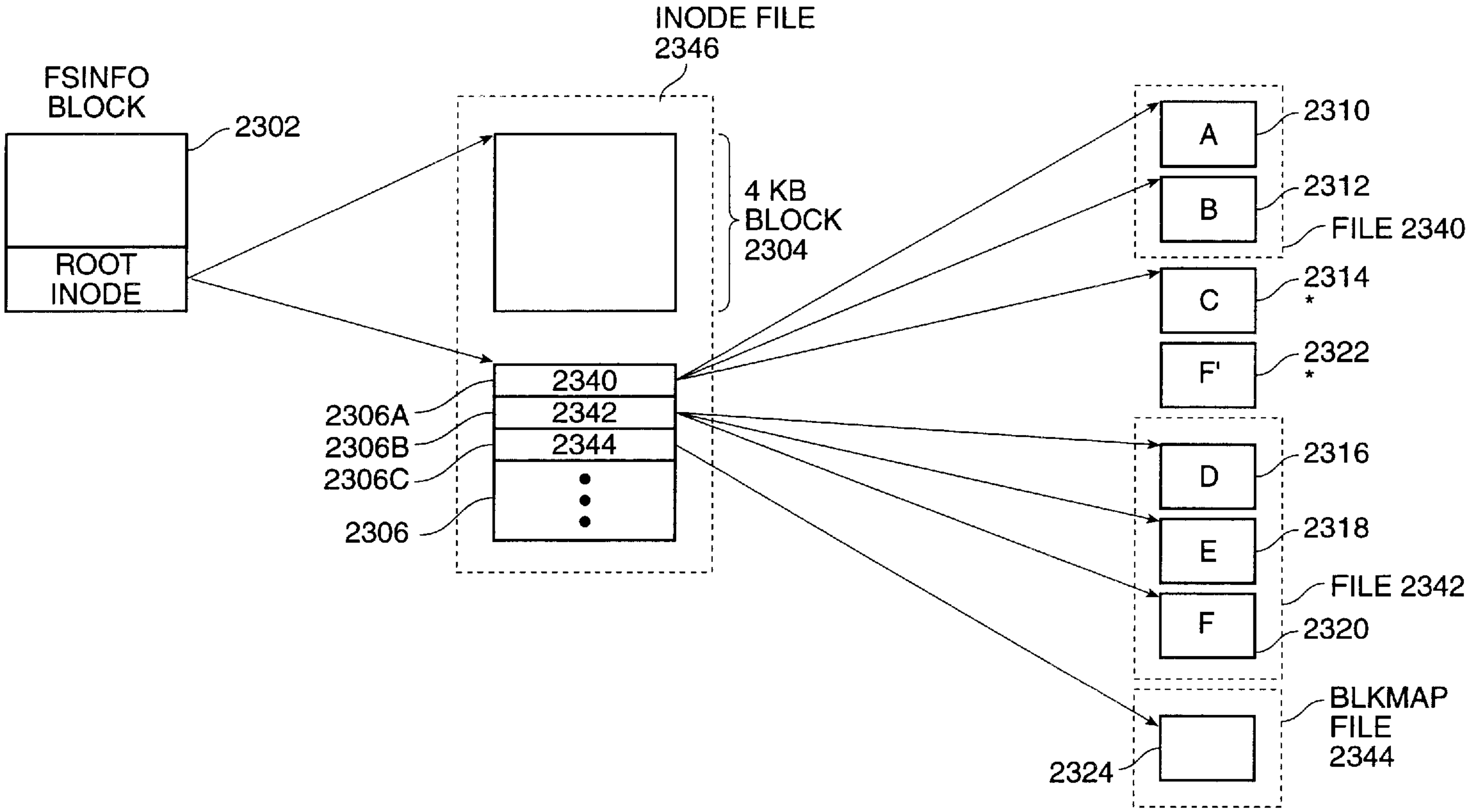
FSINFO
1612
1612A
1612C
CHECKSUM
1612B
FSINFO
1610
1610B
CHECKSUM
MISCELLANEOUS DATA 1610A
INODE 1610A OF INODE FILE 1620
INODE FILE
1630
INODE 1620A OF BLKMAP FILE 1630
BLKMAP FILE
INODE 1620B OF INOMAP FILE 1640
1640
INOMAP FILE
INODE 1620C OF ROOT DIRECTORY 1650 OF FILE SYSTEM
1650
ROOT DIRECTORY
1660
1620D
TYPICAL FILE OR DIRECTORY
PLURALITY OF INODES FOR FILES IN THE FILE SYSTEM
1620
FILE SYSTEM 1670

FIG. 16



FSINFO BLOCK
ROOT INODE
2302
INODE FILE 2346
4 KB BLOCK 2304
2340
2342
2344
2306A
2306B
2306C
2306
A
B
C
D
E
F
2310
2312
2314
2316
2318
2320
FILE 2340
FILE 2342
BLKMAP FILE 2344
2324

FIG. 17B



INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
A
B
C
F'
D
E
F
2310
2312
FILE 2340
2314
*
2322
*
2316
2318
FILE 2342
2320
BLKMAP
FILE
2344
2324

FIG. 17C

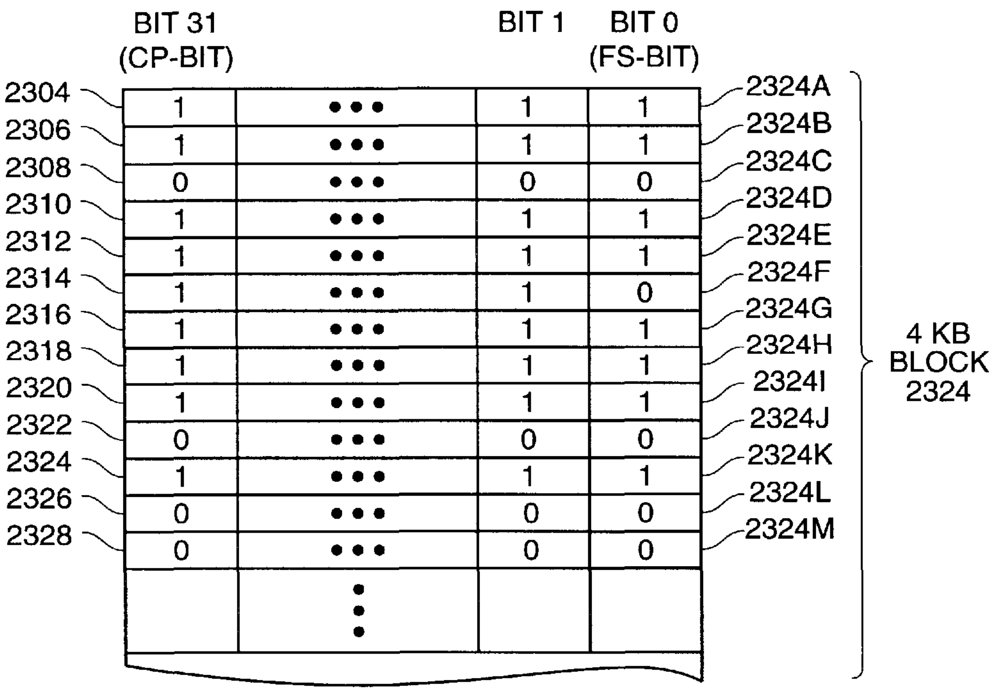


FIG. 17D

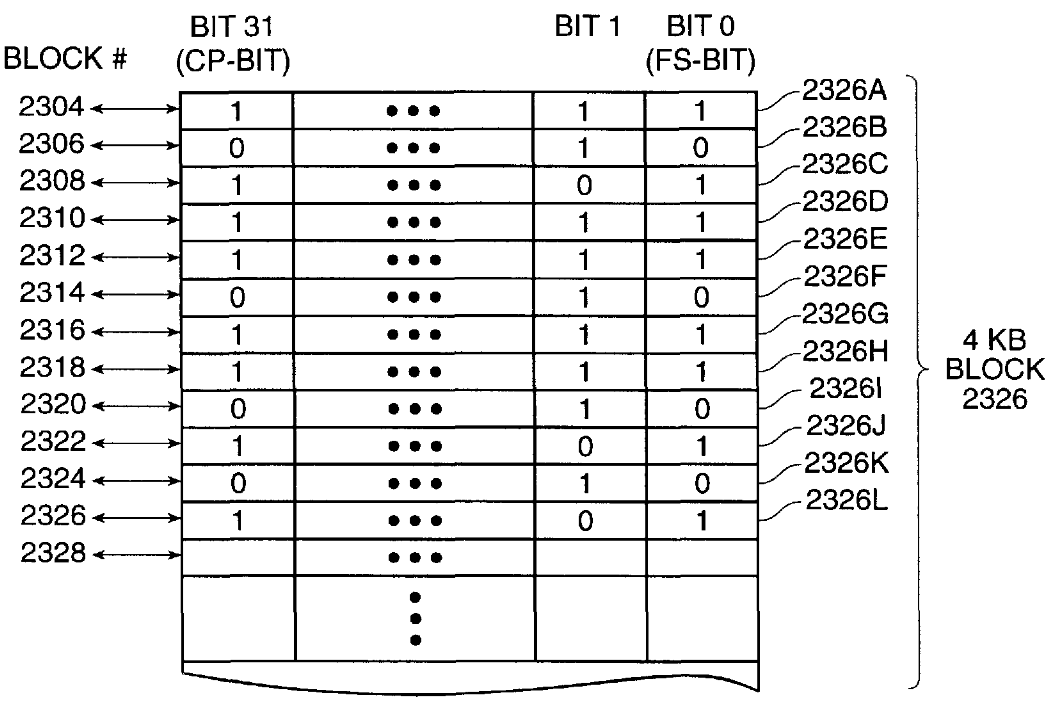
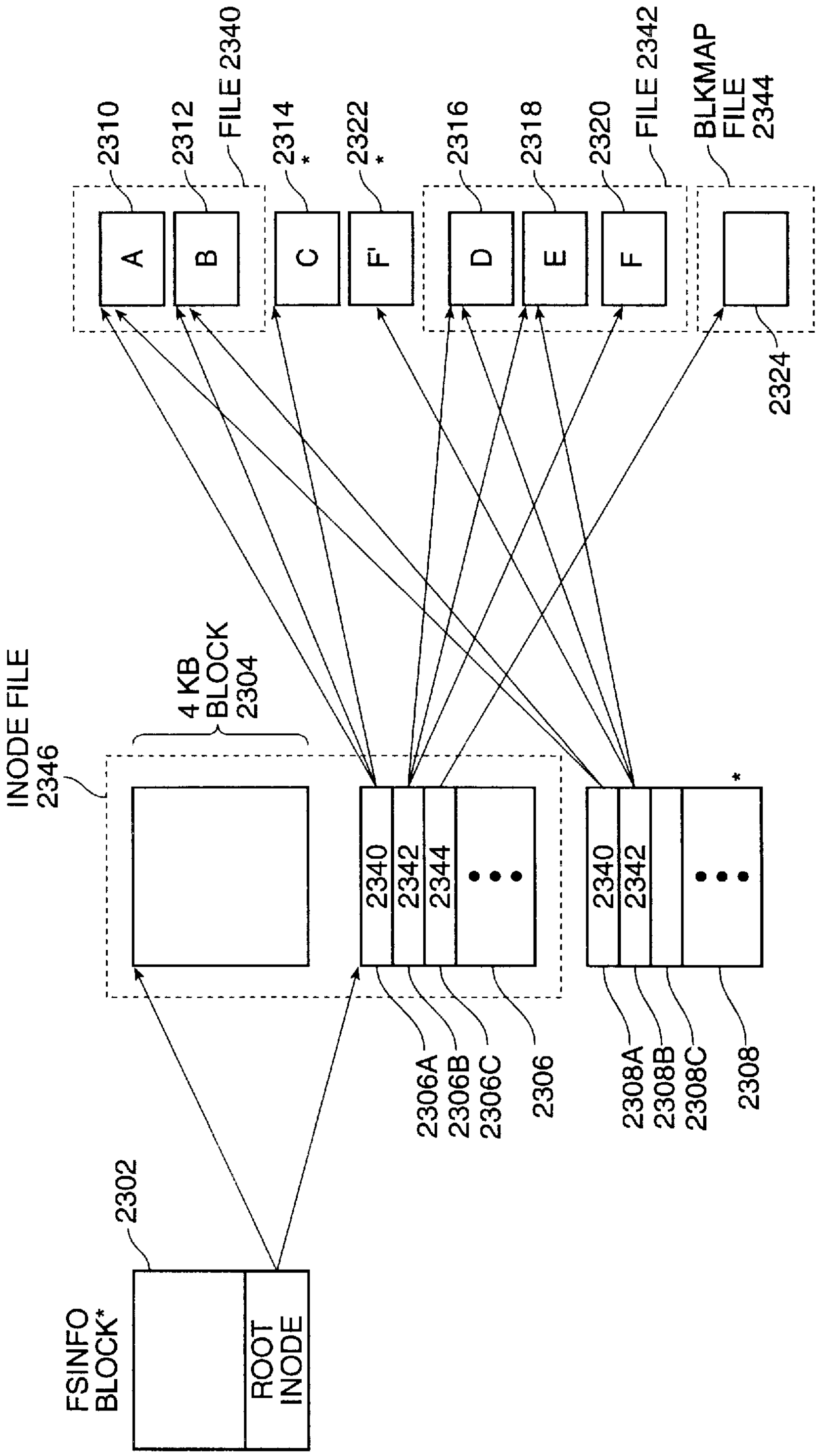


FIG. 17J



FSINFO BLOCK*
ROOT INODE
2302
INODE FILE 2346
4 KB BLOCK 2304
2340
2342
2344
2306A
2306B
2306C
2306
2308A
2308B
2308C
2308
A
B
C
F'
D
E
F
2310
2312
FILE 2340
2314
2322
2316
2318
2320
FILE 2342
BLKMAP FILE 2344
2324

FIG. 17E

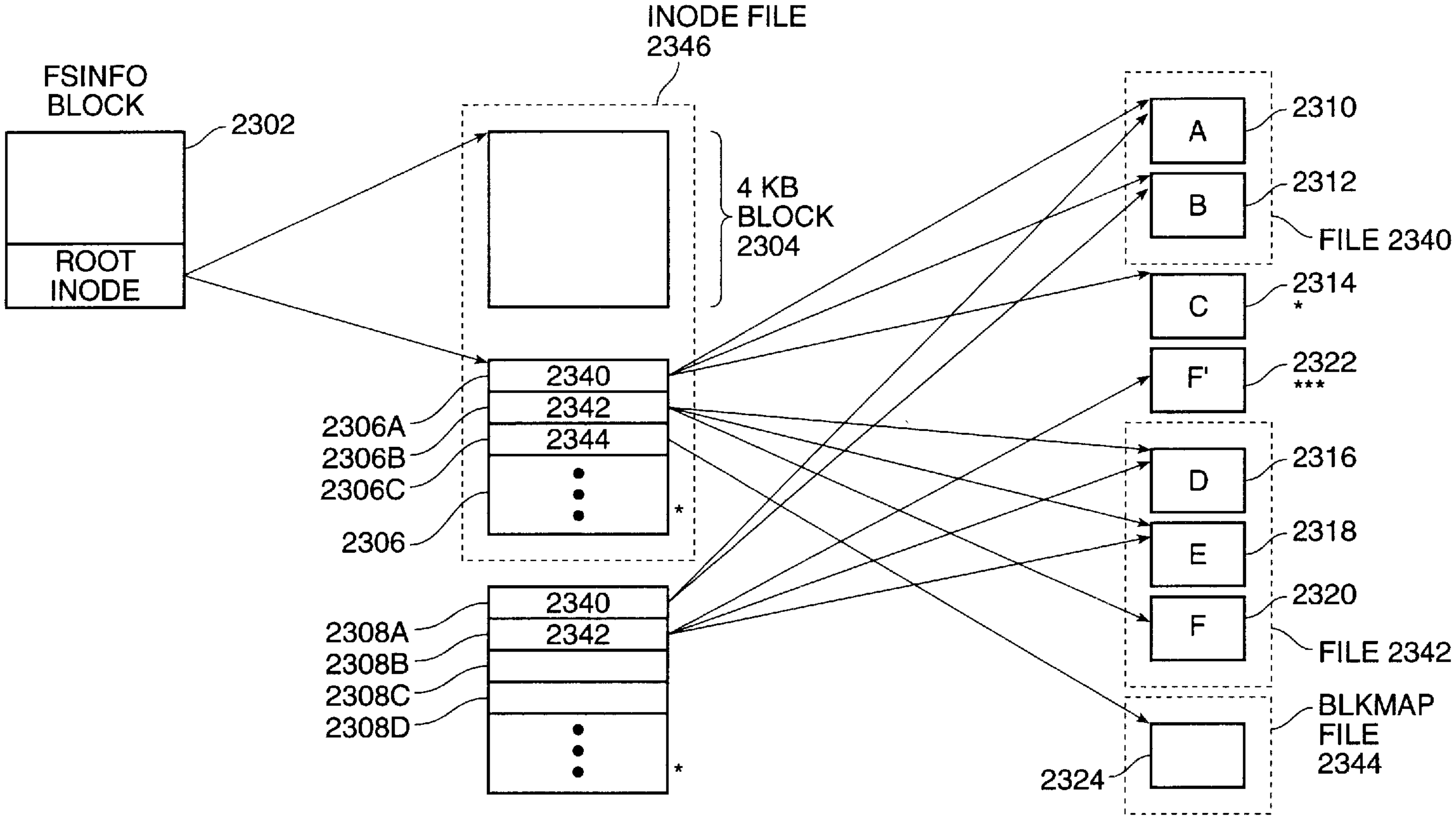

INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2340
2342
2308A
2308B
2308C
2308D
*
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
***
D
2316
E
2318
F
2320
FILE 2342
BLKMAP
FILE
2344
2324

FIG. 17F

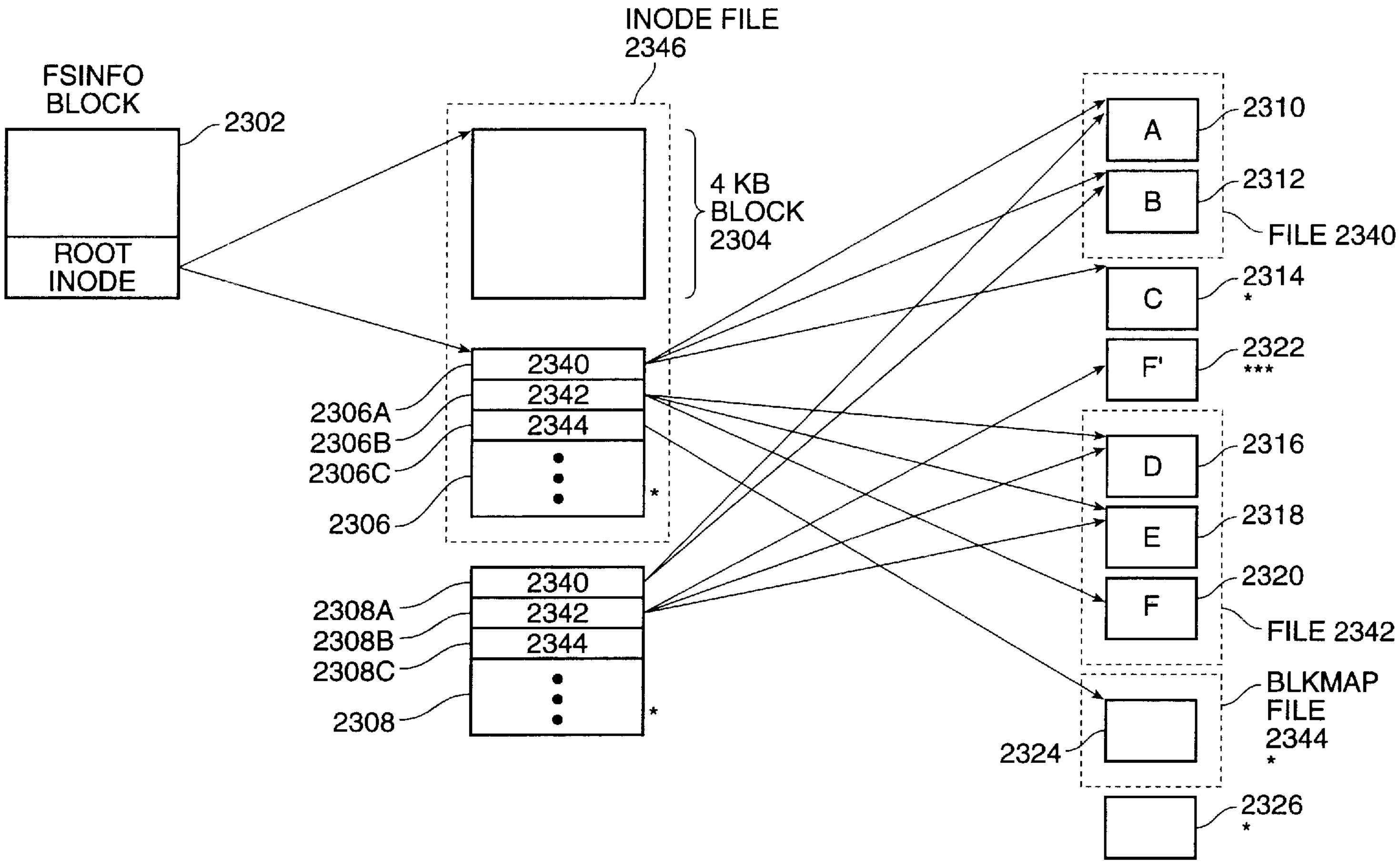

INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2308A
2308B
2308C
2308
A
B
C
F'
D
E
F
2310
2312
FILE 2340
2314
*
2322
***
2316
2318
2320
FILE 2342
BLKMAP
FILE
2344
*
2324
2326
*

FIG. 17G

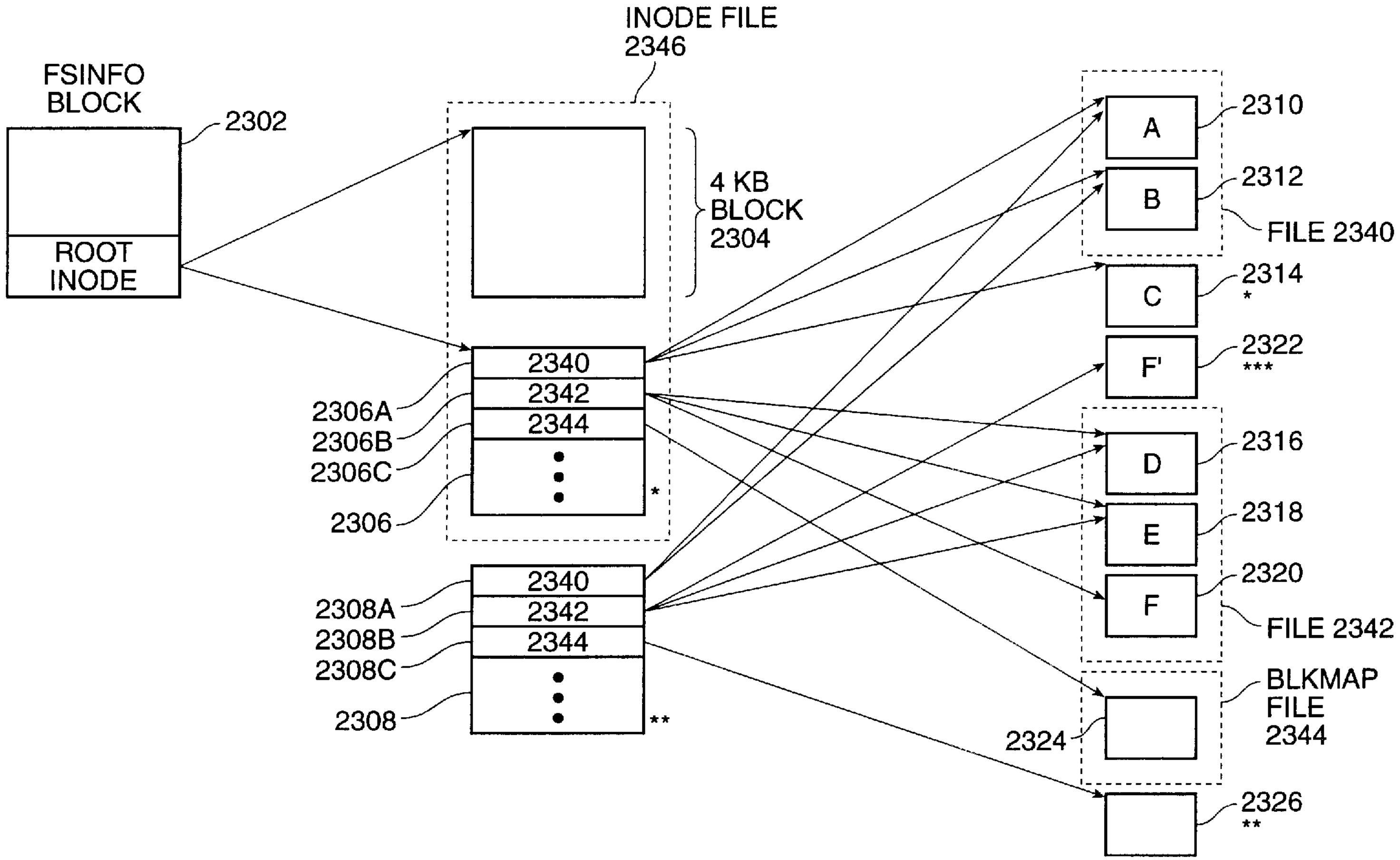
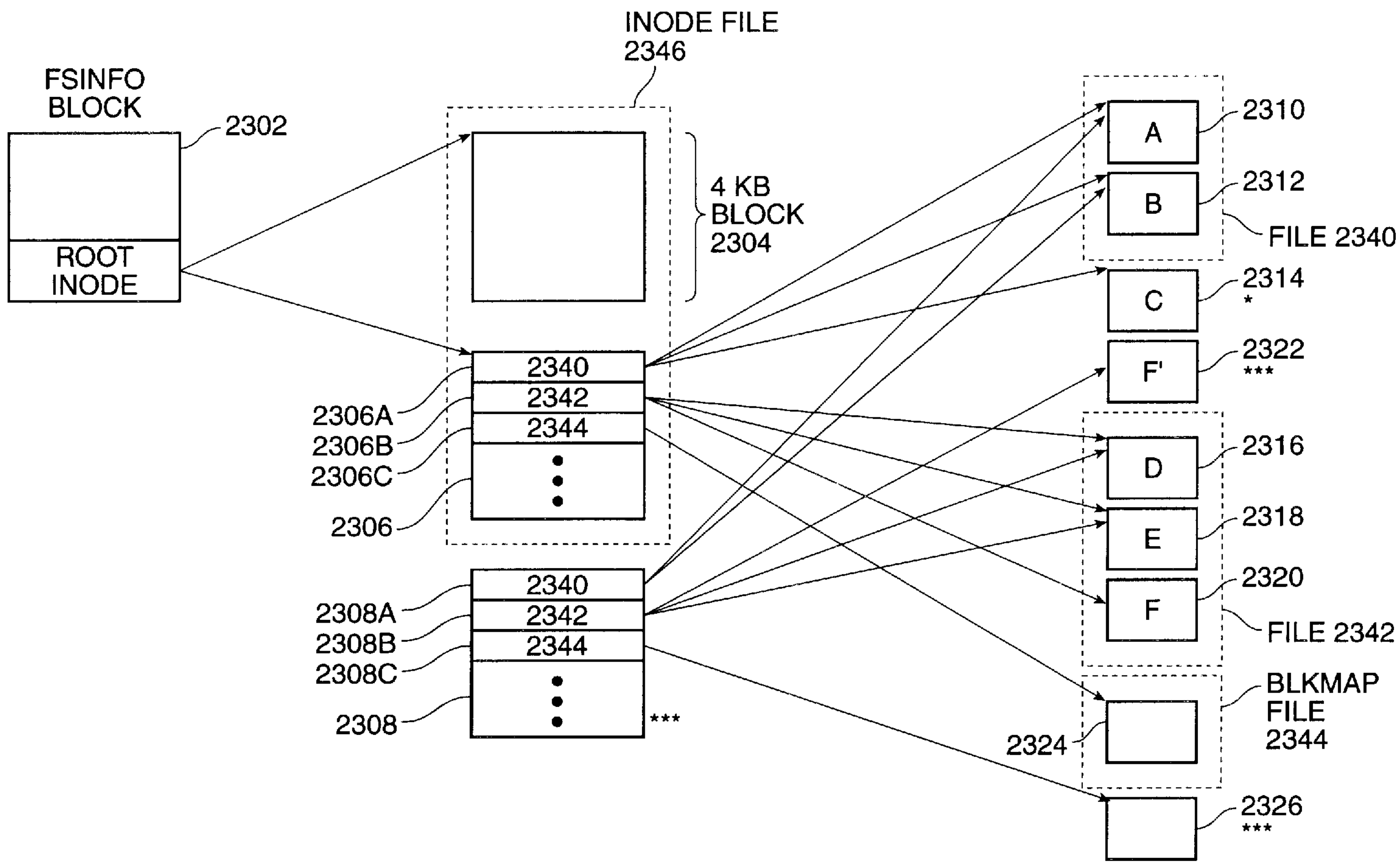

INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2340
2342
2344
2308A
2308B
2308C
2308
**
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
***
D
2316
E
2318
F
2320
FILE 2342
BLKMAP
FILE
2344
2324
2326
**

FIG. 17H



INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
2340
2342
2344
2308A
2308B
2308C
2308
***
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
***
D
2316
E
2318
F
2320
FILE 2342
BLKMAP
FILE
2344
2324
2326
***

FIG. 17K

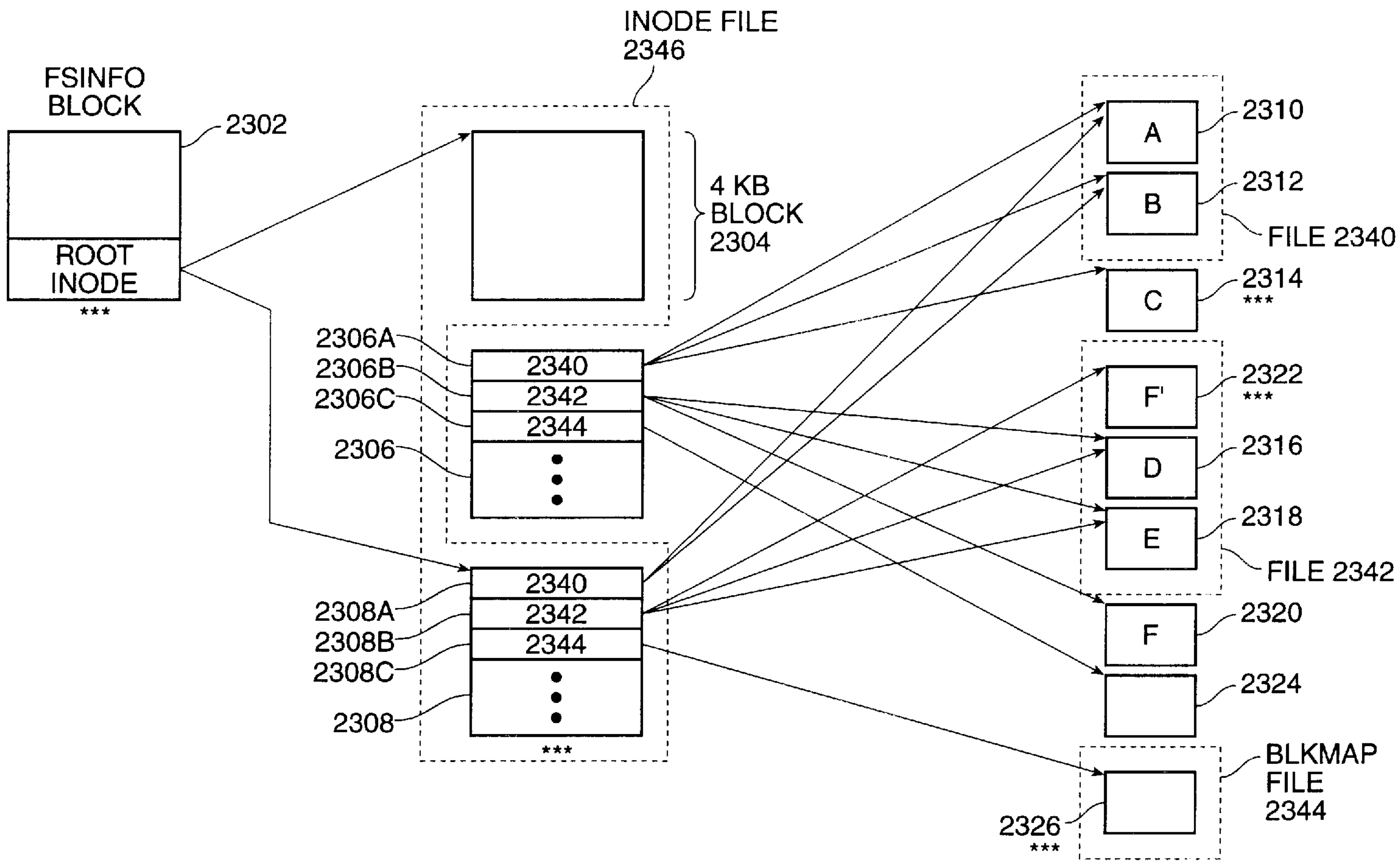

FSINFO BLOCK
2302
ROOT INODE
***
INODE FILE 2346
4 KB BLOCK 2304
2306A
2306B
2306C
2306
2340
2342
2344
2308A
2308B
2308C
2308
2340
2342
2344
***
A
2310
B
2312
FILE 2340
C
2314
***
F'
2322
***
D
2316
E
2318
FILE 2342
F
2320
2324
BLKMAP FILE 2344
2326
***

FIG. 17L

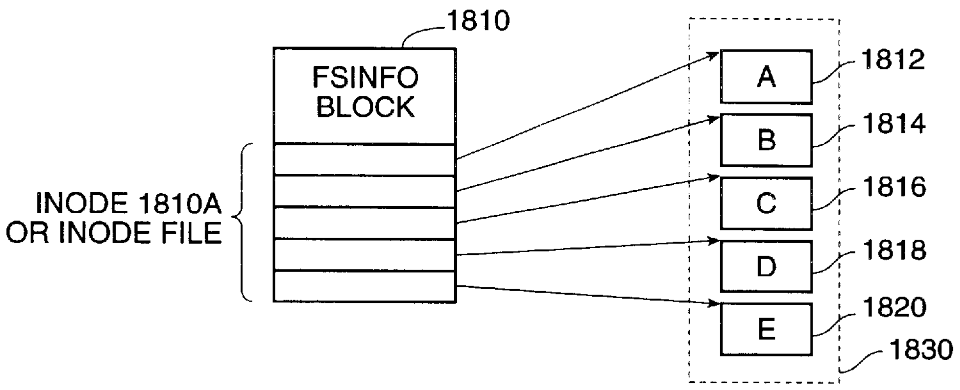


FIG. 18A

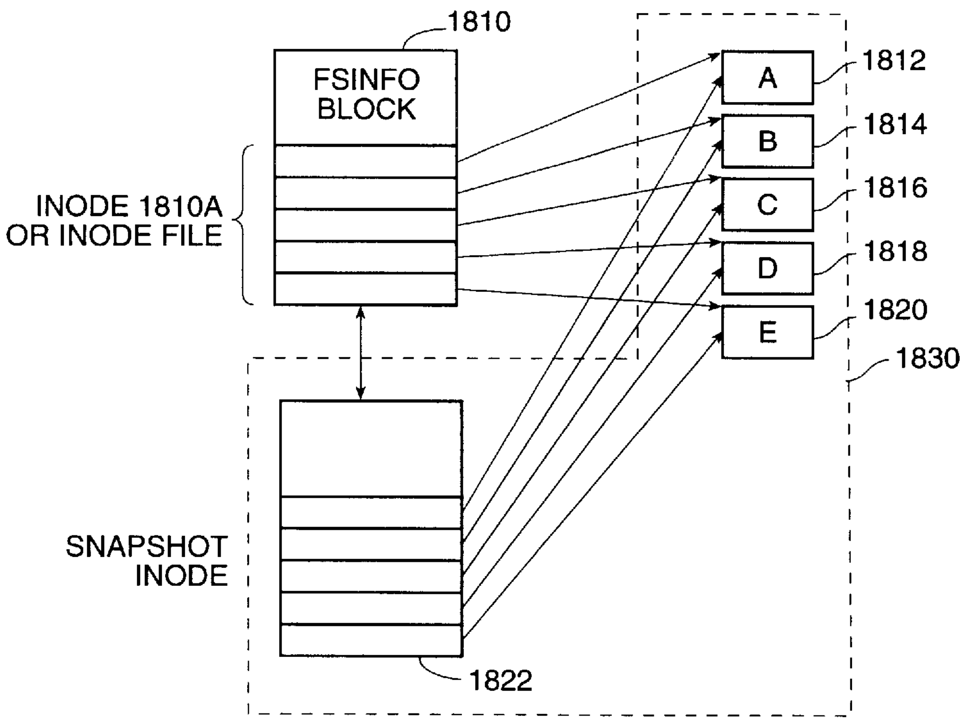


FIG. 18B

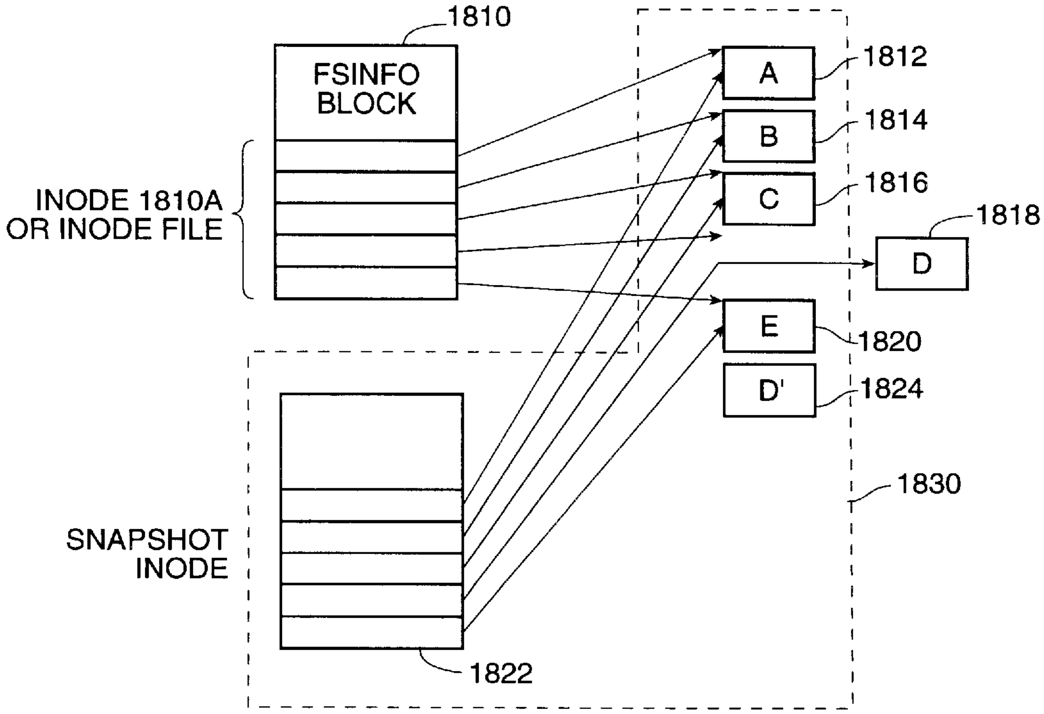

1810
FSINFO BLOCK
INODE 1810A OR INODE FILE
A
1812
B
1814
C
1816
1818
D
E
1820
D'
1824
1830
SNAPSHOT INODE
1822

FIG. 18C

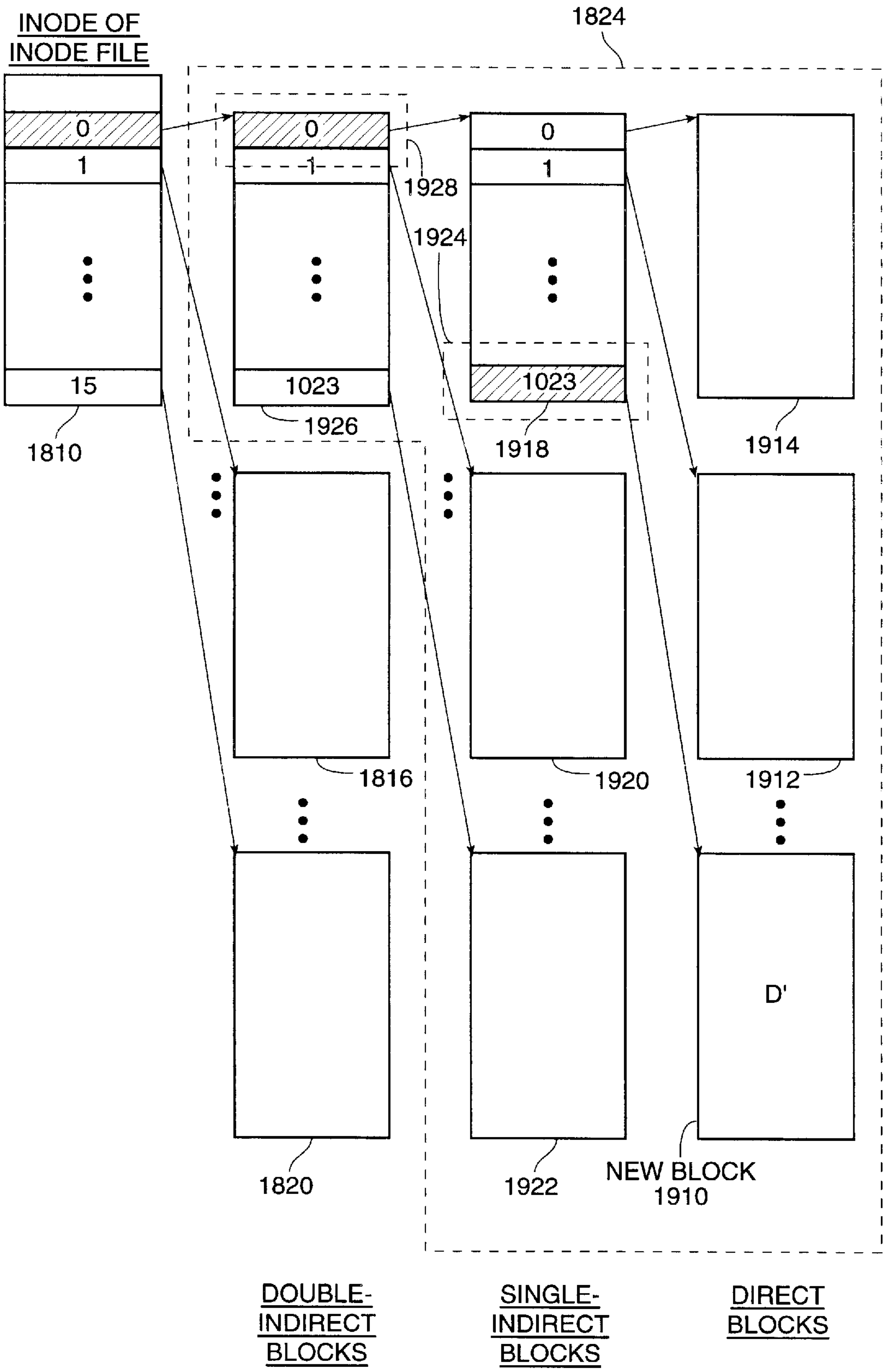

INODE OF INODE FILE
0
1
15
1810
1824
0
1
1023
1926
1928
1924
0
1
1023
1918
1914
1816
1920
1912
1820
1922
D'
NEW BLOCK 1910
DOUBLE-INDIRECT BLOCKS
SINGLE-INDIRECT BLOCKS
DIRECT BLOCKS

FIG. 19

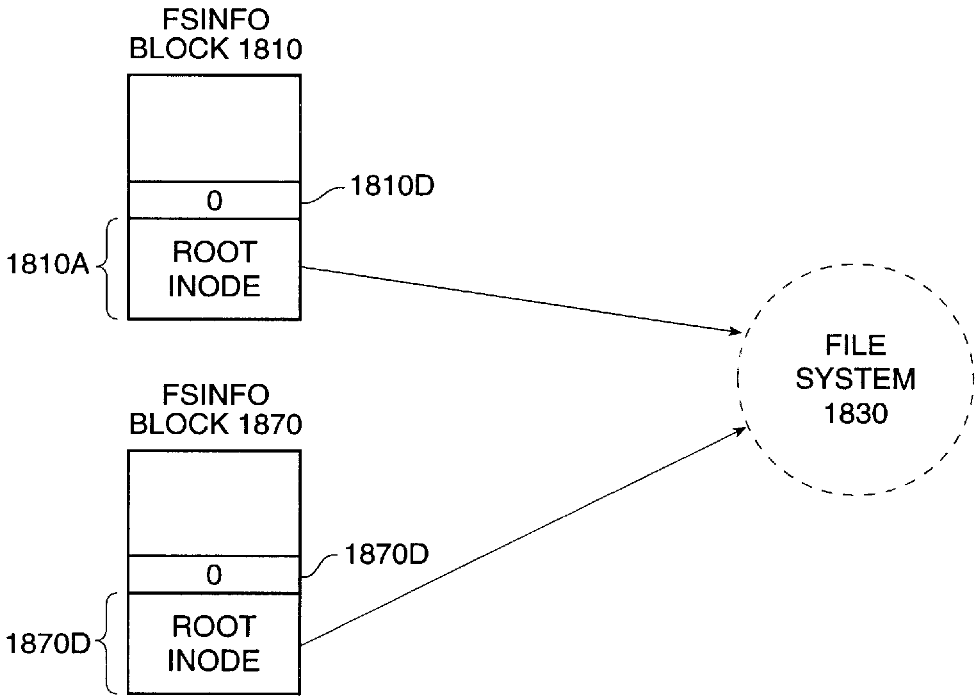


FIG. 20A

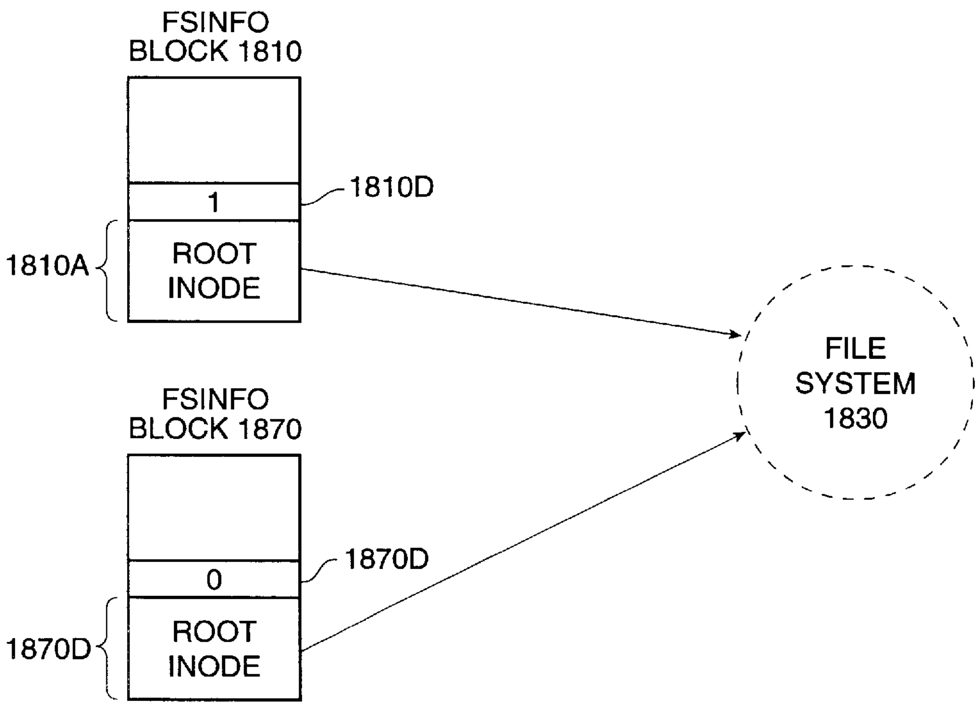


FIG. 20B

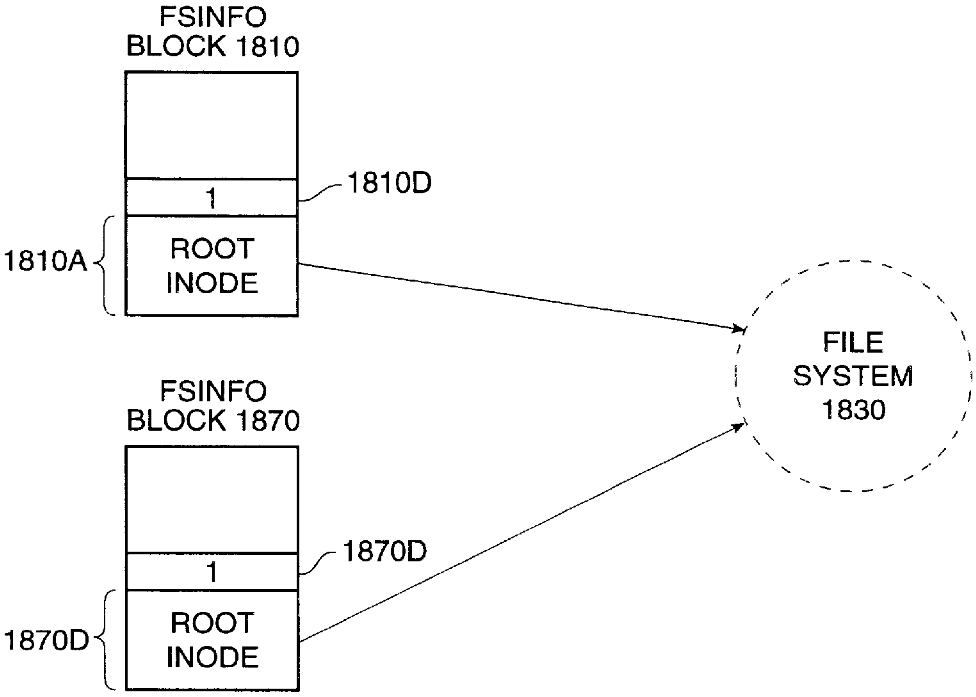


FIG. 20C

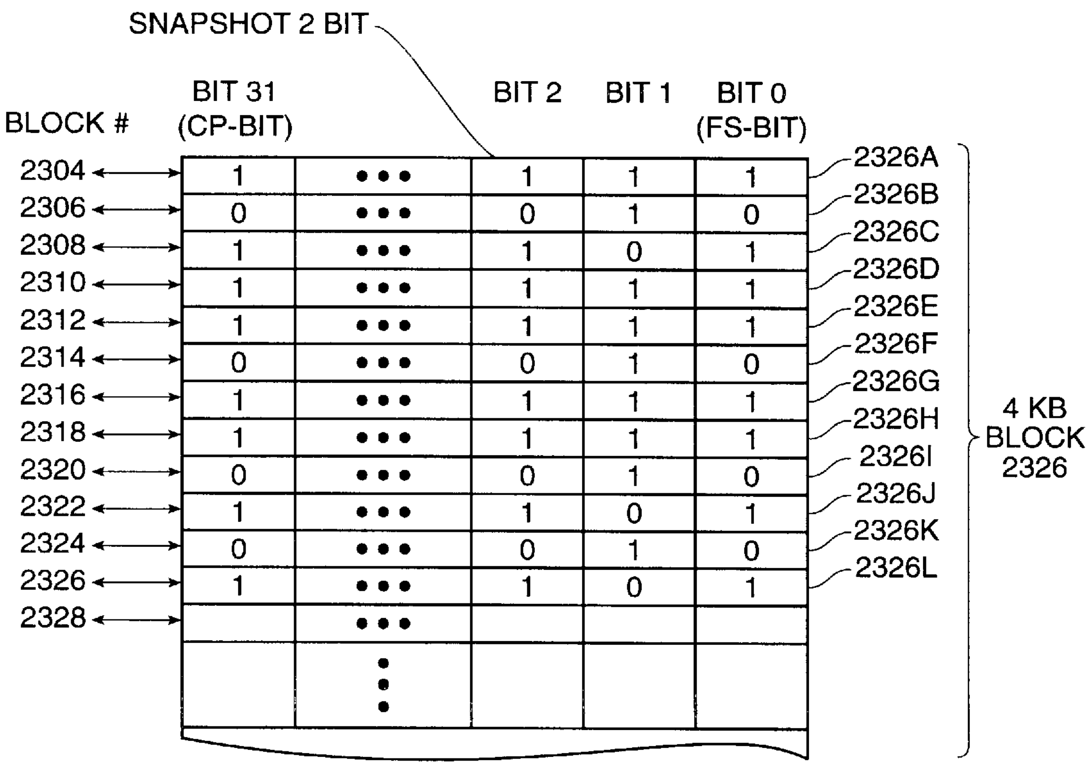
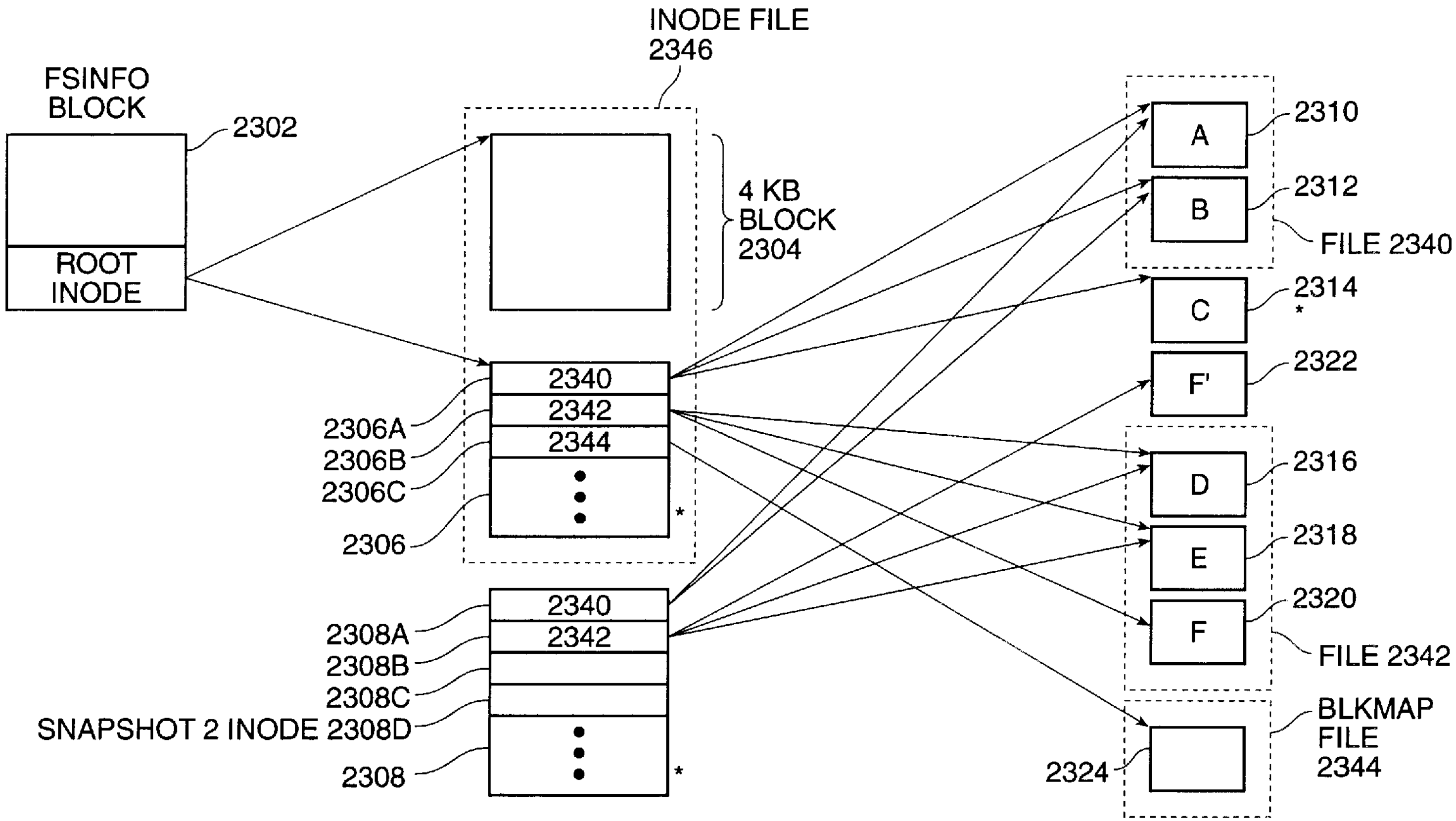


FIG. 21E



FSINFO BLOCK
2302
ROOT INODE
INODE FILE 2346
4 KB BLOCK 2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2340
2342
2308A
2308B
2308C
SNAPSHOT 2 INODE 2308D
2308
*
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
D
2316
E
2318
F
2320
FILE 2342
BLKMAP FILE 2344
2324

FIG. 21A

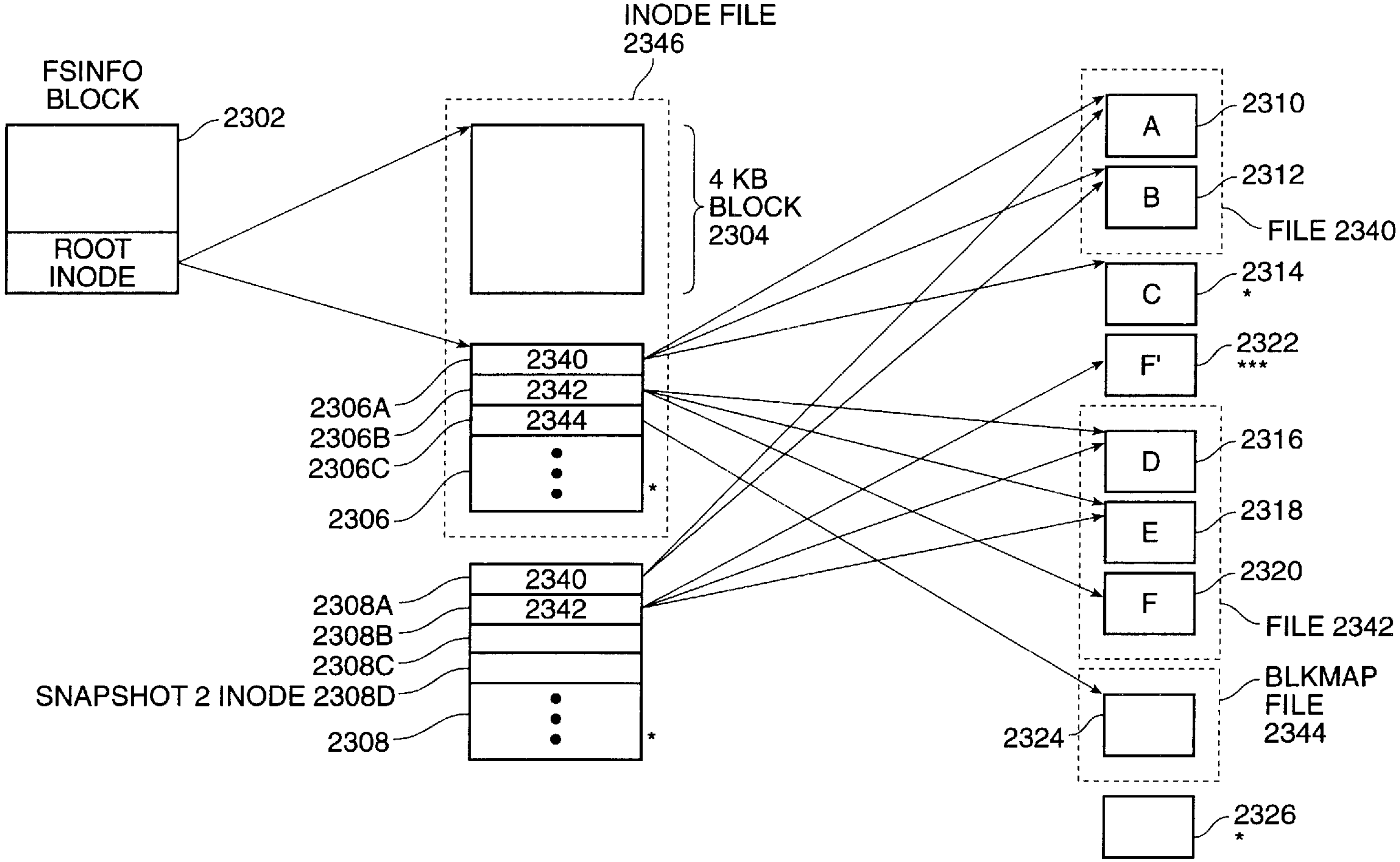

INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2340
2342
2308A
2308B
2308C
SNAPSHOT 2 INODE 2308D
2308
*
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
***
D
2316
E
2318
F
2320
FILE 2342
BLKMAP
FILE
2344
2324
2326
*

FIG. 21B

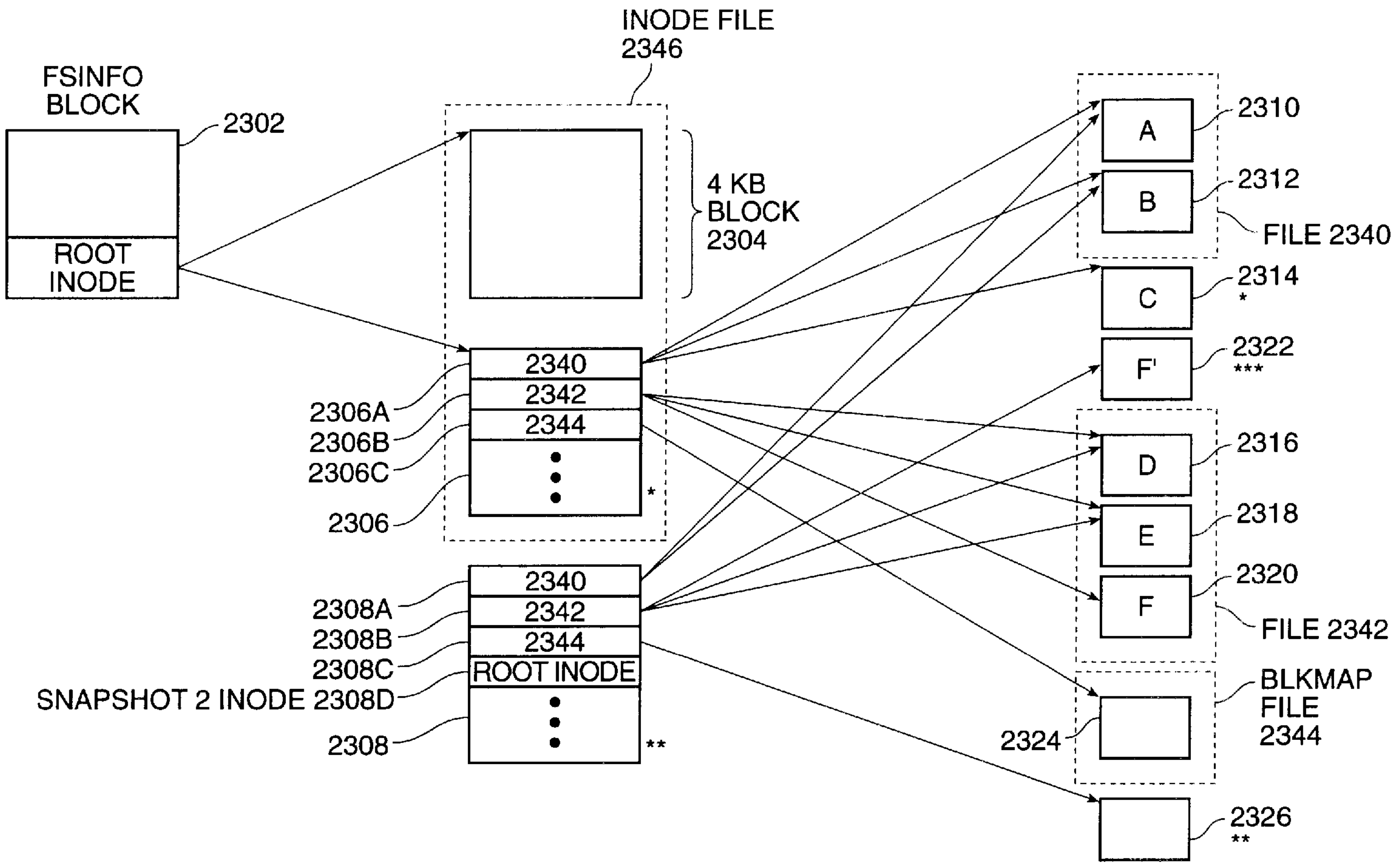

INODE FILE
2346
FSINFO
BLOCK
2302
ROOT
INODE
4 KB
BLOCK
2304
2340
2342
2344
2306A
2306B
2306C
2306
*
2340
2342
2344
ROOT INODE
2308A
2308B
2308C
SNAPSHOT 2 INODE 2308D
2308
**
A
2310
B
2312
FILE 2340
C
2314
*
F'
2322
***
D
2316
E
2318
F
2320
FILE 2342
BLKMAP
FILE
2344
2324
2326
**

FIG. 21C

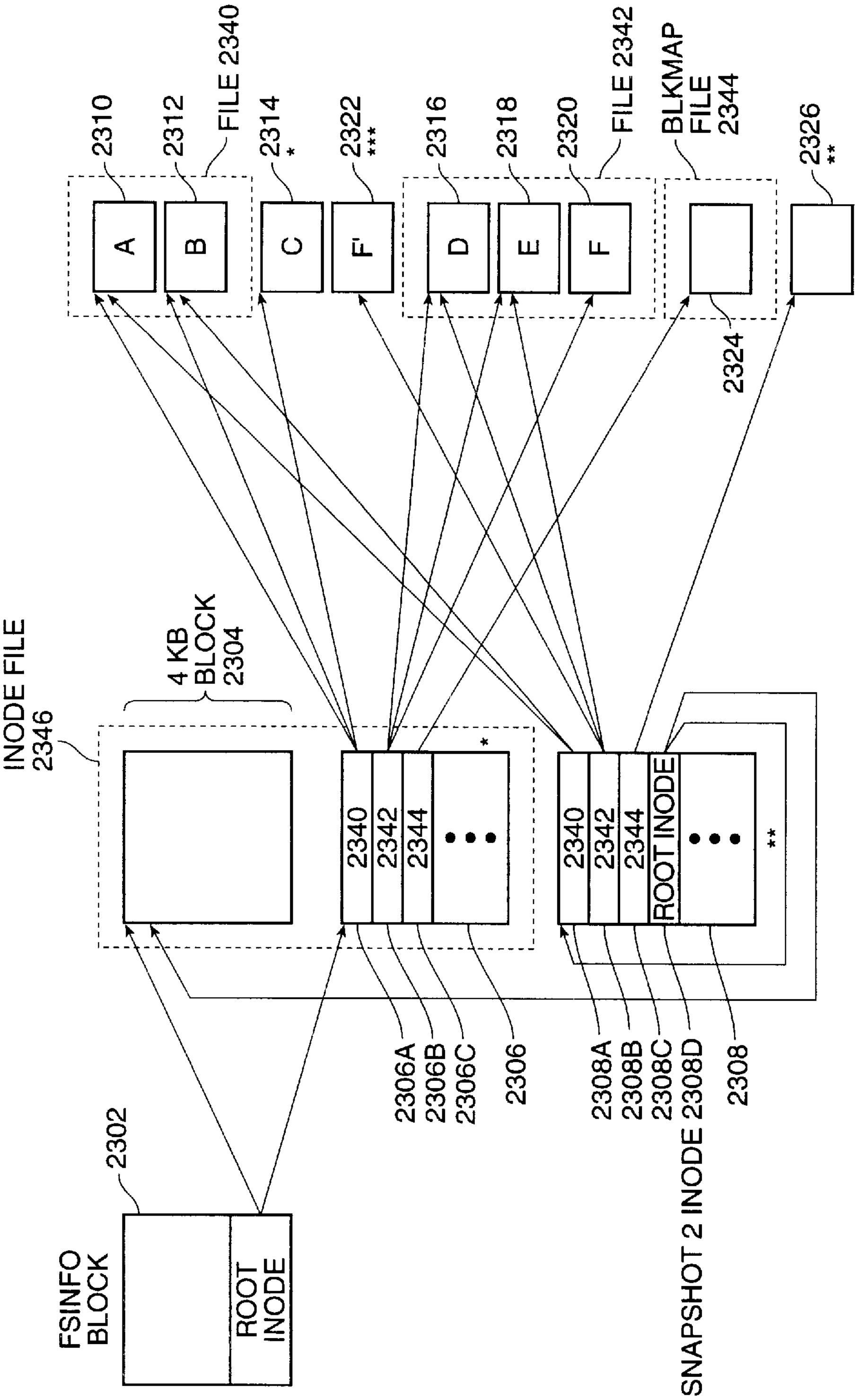
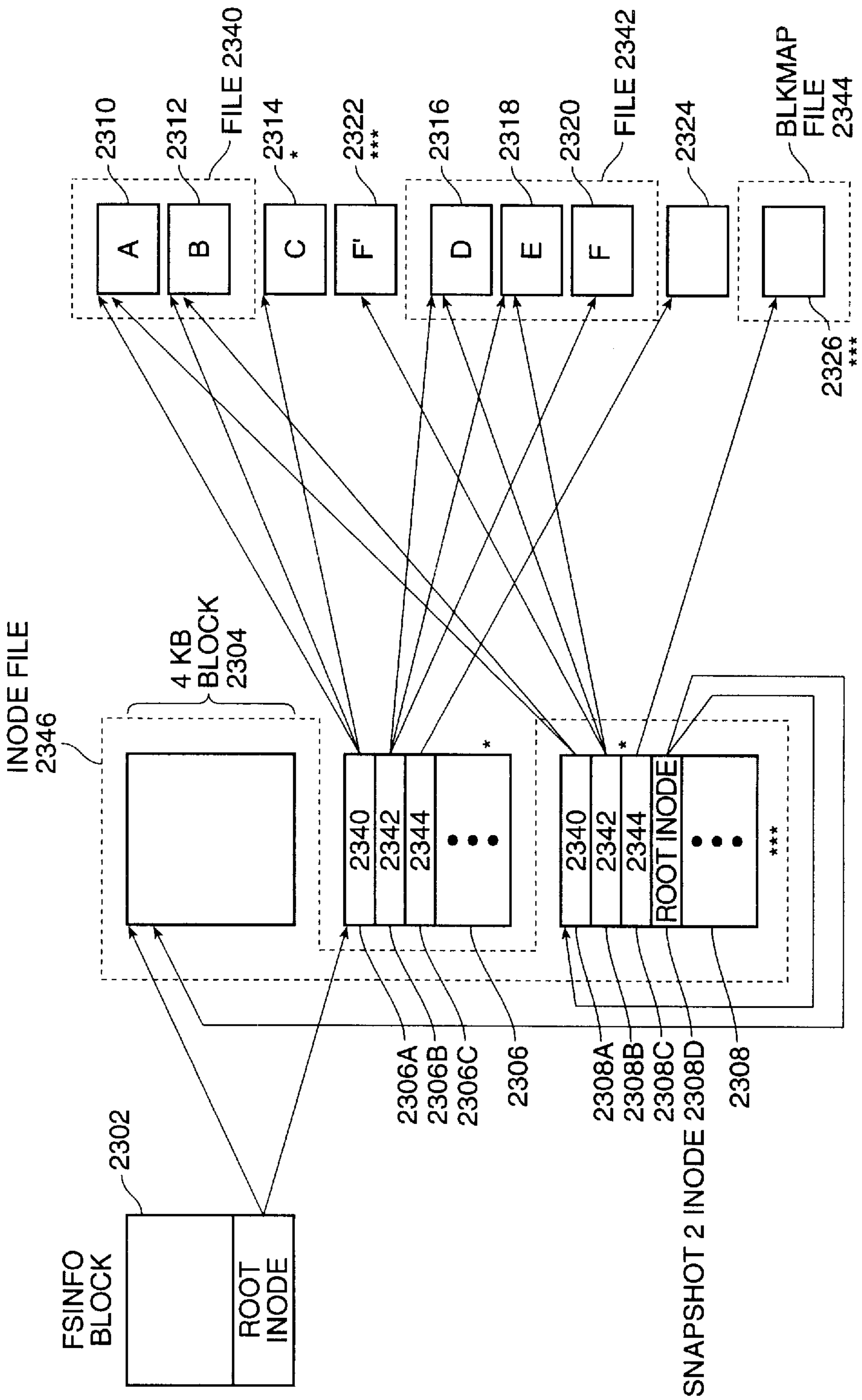
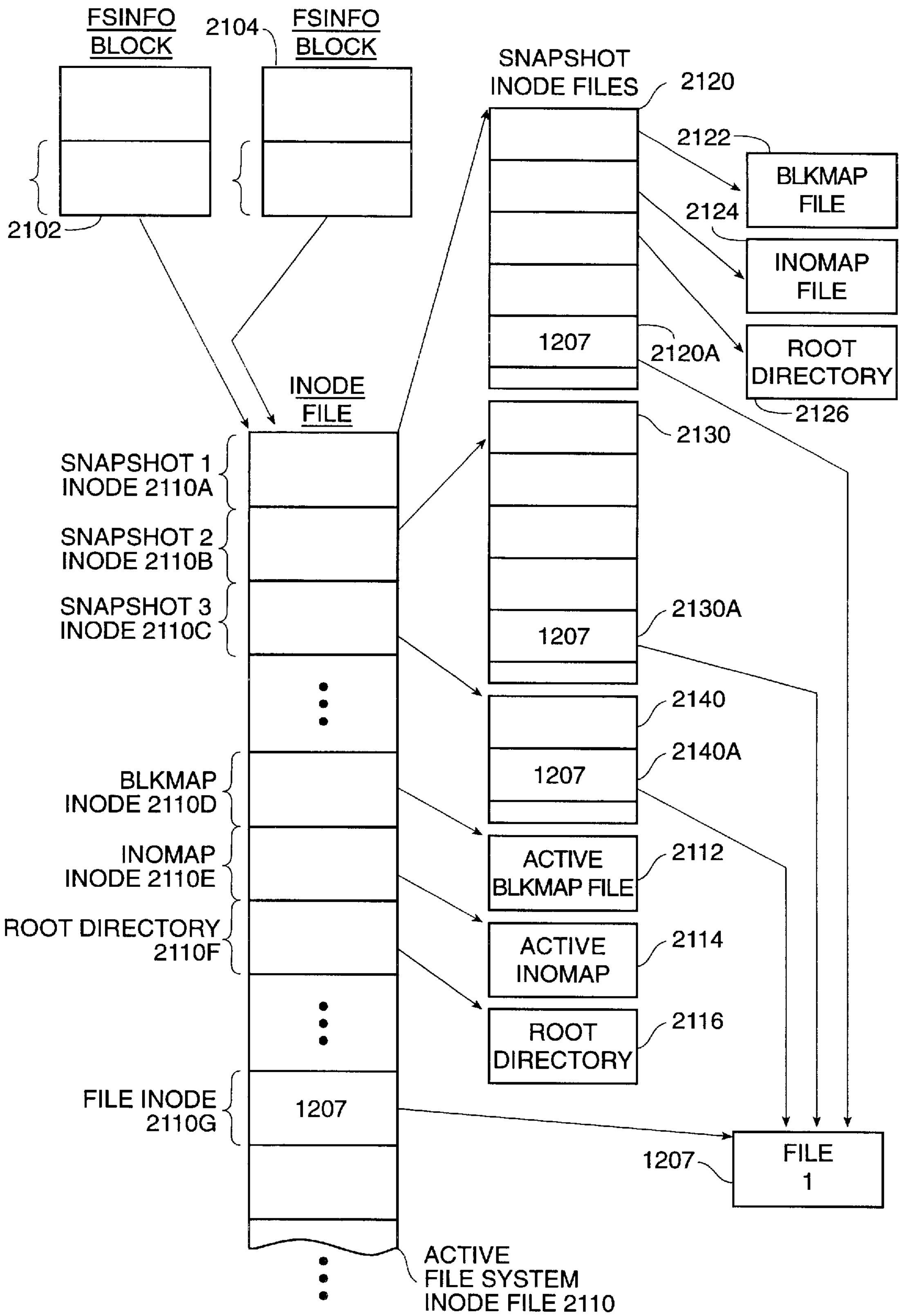

FSINFO BLOCK
2302
ROOT INODE
INODE FILE 2346
4 KB BLOCK 2304
2340
2342
2344
*
2306A
2306B
2306C
2306
2340
2342
2344
ROOT INODE
**
2308A
2308B
2308C
SNAPSHOT 2 INODE 2308D
2308
A
B
FILE 2340
2310
2312
C
2314
*
F'
2322
***
D
E
F
2316
2318
2320
FILE 2342
BLKMAP FILE 2344
2324
2326
**

FIG. 21D



FSINFO BLOCK
ROOT INODE
2302
INODE FILE 2346
4 KB BLOCK 2304
2340
2342
2344
2306A
2306B
2306C
2306
2308A
2308B
2308C
2308D
2308
SNAPSHOT 2 INODE
ROOT INODE
A
B
C
F'
D
E
F
2310
2312
FILE 2340
2314
2322
2316
2318
2320
FILE 2342
2324
BLKMAP FILE 2344
2326

FIG. 21F



FSINFO BLOCK
2104
FSINFO BLOCK
2102
SNAPSHOT INODE FILES
2120
2122
BLKMAP FILE
2124
INOMAP FILE
1207
2120A
ROOT DIRECTORY
2126
INODE FILE
SNAPSHOT 1 INODE 2110A
SNAPSHOT 2 INODE 2110B
SNAPSHOT 3 INODE 2110C
2130
1207
2130A
2140
1207
2140A
BLKMAP INODE 2110D
INOMAP INODE 2110E
ROOT DIRECTORY 2110F
ACTIVE BLKMAP FILE
2112
ACTIVE INOMAP
2114
ROOT DIRECTORY
2116
FILE INODE 2110G
1207
1207
FILE 1
ACTIVE FILE SYSTEM INODE FILE 2110

FIG. 22

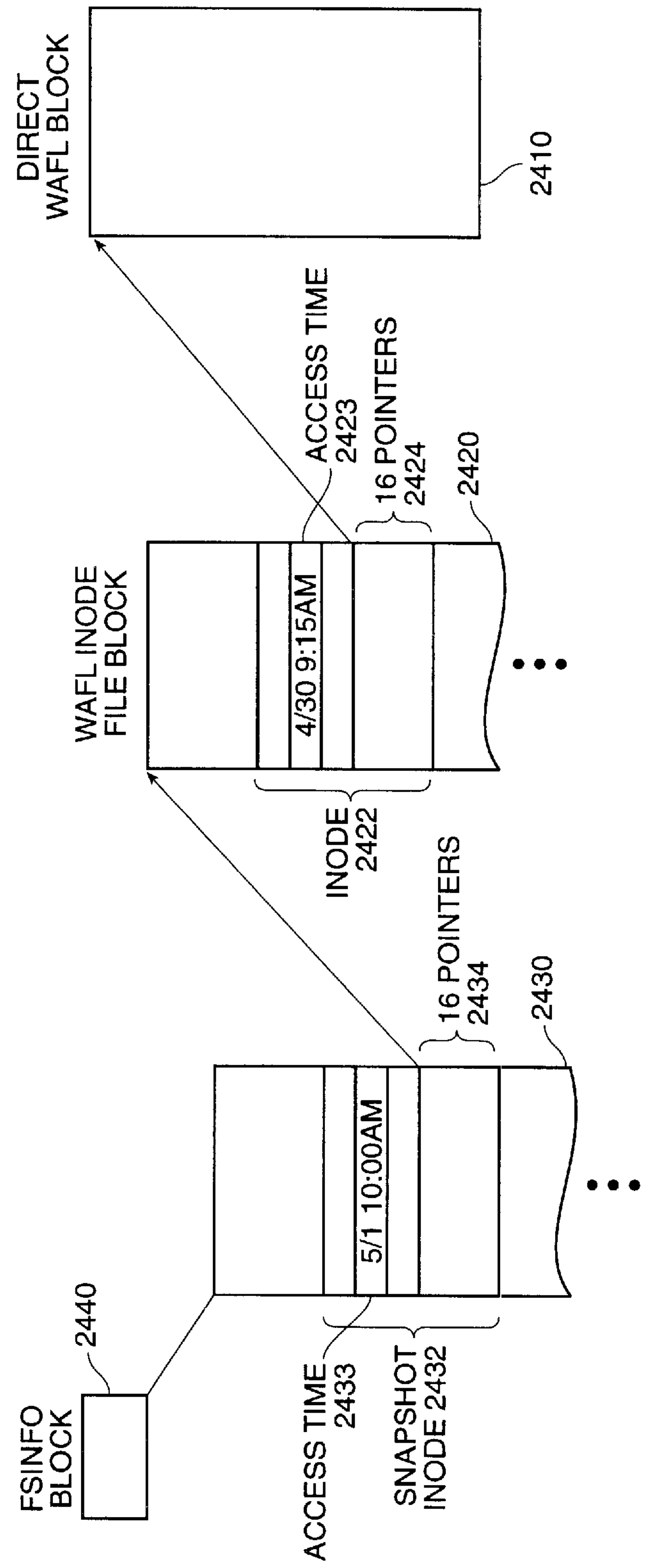

DIRECT WAFL BLOCK
2410
ACCESS TIME 2423
16 POINTERS 2424
2420
WAFL INODE FILE BLOCK
4/30 9:15AM
INODE 2422
16 POINTERS 2434
2430
5/1 10:00AM
FSINFO BLOCK
2440
ACCESS TIME 2433
SNAPSHOT INODE 2432

FIG. 23A

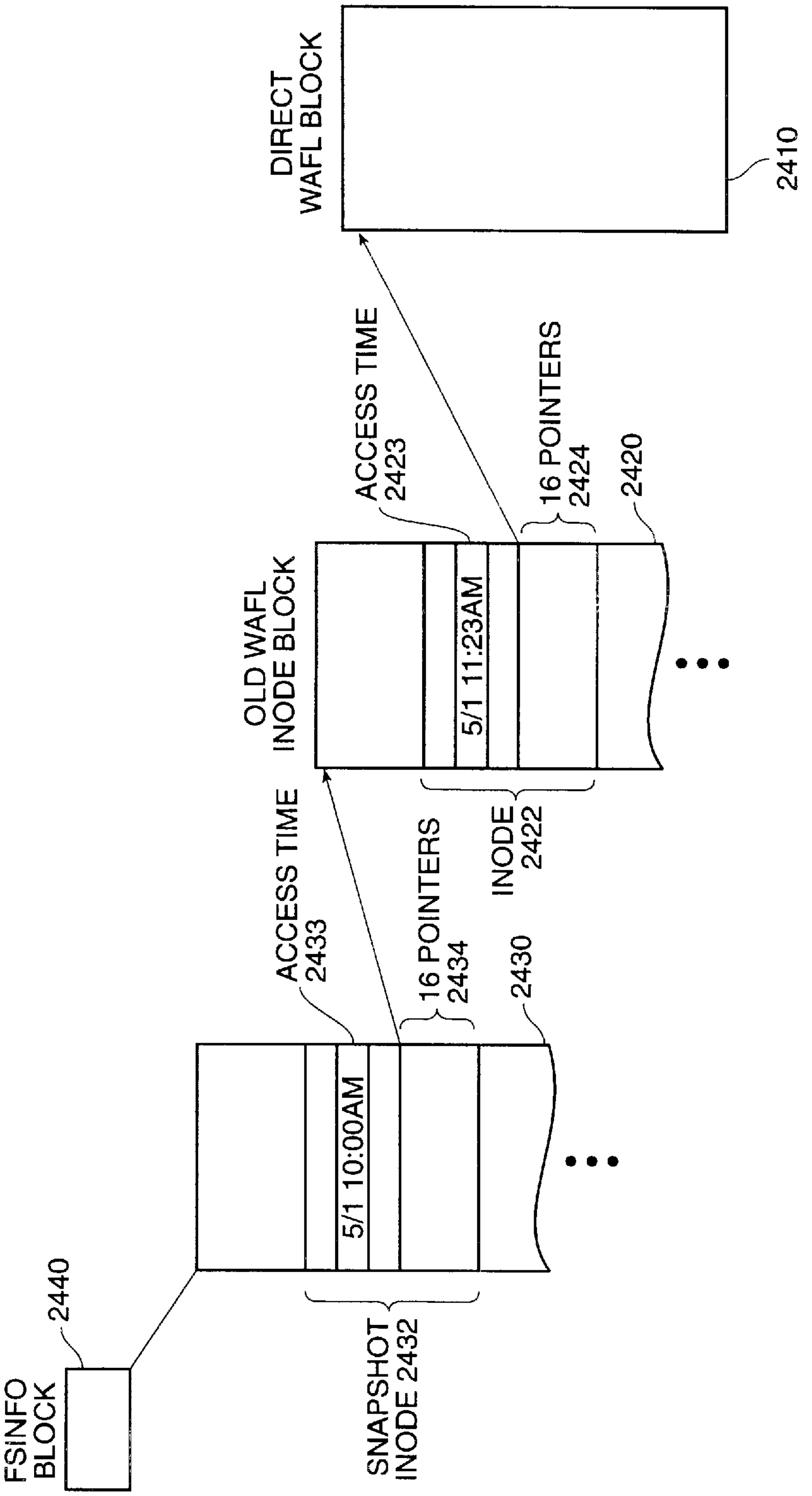

DIRECT WAFL BLOCK
2410
ACCESS TIME 2423
16 POINTERS 2424
2420
OLD WAFL INODE BLOCK
5/1 11:23AM
INODE 2422
ACCESS TIME 2433
16 POINTERS 2434
2430
5/1 10:00AM
SNAPSHOT INODE 2432
2440
FSINFO BLOCK

FIG. 23B

METHOD FOR MAINTAINING CONSISTENT STATES OF A FILE SYSTEM AND FOR CREATING USER-ACCESSIBLE READ-ONLY COPIES OF A FILE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

This is a file-wrapper continuation of patent application Ser. No. 08/071,643, filed Jun. 3, 1993, now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to the field of methods and apparatus for maintaining a consistent file system and for creating read-only copies of the file system.

2. Background Art

All file systems must maintain consistency in spite of system failure. A number of different consistency techniques have been used in the prior art for this purpose.

One of the most difficult and time consuming issues in managing any file server is making backups of file data. Traditional solutions have been to copy the data to tape or other off-line media. With some file systems, the file server must be taken off-line during the backup process in order to ensure that the backup is completely consistent. A recent advance in backup is the ability to quickly "clone" (i.e., a prior art method for creating a read-only copy of the file system on disk) a file system, and perform a backup from the clone instead of from the active file system. With this type of file system, it allows the file server to remain on-line during the backup.

File System Consistency

A prior art file system is disclosed by Chuntani et al. in an article entitled *The Episode File System,* USENIX, Winter 1992, at pages 43–59. The article describes the Episode file system which is a file system using meta-data (i.e., inode tables, directories, bitmaps, and indirect blocks). It can be used as a stand-alone or as a distributed file system. Episode supports a plurality of separate file system hierarchies. Episode refers to the plurality of file systems collectively as an "aggregate". In particular, Episode provides a clone of each file system for slowly changing data.

In Episode, each logical file system contains an "anode" table. An anode table is the equivalent of an inode table used in file systems such as the Berkeley Fast File System. It is a 252-byte structure. Anodes are used to store all user data as well as meta-data in the Episode file system. An anode describes the root directory of a file system including auxiliary files and directories. Each such file system in Episode is referred to as a "fileset". All data within a fileset is locatable by iterating through the anode table and processing each file in turn. Episode creates a read-only copy of a file system, herein referred to as a "clone", and shares data with the active file system using Copy-On-Write (COW) techniques.

Episode uses a logging technique to recover a file system (s) after a system crashes. Logging ensures that the file system meta-data are consistent. A bitmap table contains information about whether each block in the file system is allocated or not. Also, the bitmap table indicates whether or not each block is logged. All meta-data updates are recorded in a log "container" that stores a transaction log of the aggregate. The log is processed as a circular buffer of disk blocks. The transaction logging of Episode uses logging techniques originally developed for databases to ensure file system consistency. This technique uses carefully ordered writes and a recovery program that are supplemented by database techniques in the recovery program.

Other prior art systems including JFS of IBM and VxFS of Veritas Corporation use various forms of transaction logging to speed the recovery process, but still require a recovery process.

Another prior art method is called the "ordered write" technique. It writes all disk blocks in a carefully determined order so that damage is minimized when a system failure occurs while performing a series of related writes. The prior art attempts to ensure that inconsistencies that occur are harmless. For instance, a few unused blocks or inodes may be marked as allocated. The primary disadvantage of this technique is that the restrictions it places on disk order make it hard to achieve high performance.

Yet another prior art system is an elaboration of the second prior art method referred to as an "ordered write with recovery" technique. In this method, inconsistencies can be potentially harmful. However, the order of writes is restricted so that inconsistencies can be found and fixed by a recovery program. Examples of this method include the original UNIX file system and Berkeley Fast File System (FFS). This technique does not reduce disk ordering sufficiently to eliminate the performance penalty of disk ordering. Another disadvantage is that the recovery process is time consuming. It typically is proportional to the size of the file system. Therefore, for example, recovering a 5 gigabyte FFS file system requires an hour or more to perform.

File System Clones

FIG. **1** is a prior art diagram for the Episode file system illustrating the use of copy-on-write (COW) techniques for creating a fileset clone. Anode **110** comprises a first pointer **110**A having a COW bit that is set. Pointer **110**A references data block **114** directly. Anode **110** comprises a second pointer **110**B having a COW bit that is cleared. Pointer **110**B of anode references indirect block **112**. Indirect block **112** comprises a pointer **112**A that references data block **124** directly. The COW bit of pointer **112**A is set. Indirect block **112** comprises a second pointer **112**B that references data block **126**. The COW bit of pointer **112**B is cleared.

A clone anode **120** comprises a first pointer **120**A that references data block **114**. The COW bit of pointer **120**A is cleared. The second pointer **120**B of clone anode **120** references indirect block **122**. The COW bit of pointer **120**B is cleared. In turn, indirect block **122** comprises a pointer **122**A that references data block **124**. The COW bit of pointer **122**A is cleared.

As illustrated in FIG. **1**, every direct pointer **110**A, **112**A–**112**B, **120**A, and **122**A and indirect pointer **110**B and **120**B in the Episode file system contains a COW bit. Blocks that have not been modified since the clone was created are contained in both the active file system and the clone, and have set (**1**) COW bits. The COW bit is cleared (**0**) when a block that is referenced to by the pointer has been modified and, therefore, is part of the active file system but not the done.

When a clone is created in Episode, the entire anode table is copied, along with all indirect blocks that the anodes reference. The new copy describes the clone, and the original copy continues to describe the active file system. In the original copy, the COW bits in all pointers are set to indicate that they point to the same data blocks as the clone. Thus, when anode **110** in FIG. **1** was cloned, it was copied to clone anode **120**, and indirect block **112** was copied to done indirect block **122**. In addition, the COW bit of pointer **112**A

was set to indicate that indirect blocks **112** and **122** both point to data block **124**. In FIG. **1**, data block **124** has not been modified since the clone was created, so it is still referenced by pointers **112**A and **112**B, and the COW bit in **112**A is still set. Data block **126** is not part of the done, and so pointer **112**B which references it does not have its COW bit set.

When an Episode clone is created, every anode and every indirect block in the file system must be copied, which consumes many mega-bytes and takes a significant mount of time to write to disk.

A fileset "clone" is a read-only copy of an active fileset wherein the active fileset is readable and writable. Clones are implemented using COW techniques, and share data blocks with an active fileset on a block-by-block basis. Episode implements cloning by copying each anode stored in a fileset. When initially cloned, both the writable anode of the active fileset and the cloned anode both point to the same data block(s). However, the disk addresses for direct and indirect blocks in the original anode are tagged as COW. Thus, an update to the writable fileset does not affect the done. When a COW block is modified, a new block is allocated in the file system and updated with the modification. The COW flag in the pointer to this new block is cleared.

The prior art Episode system creates clones that duplicate the entire inode file and all of the indirect blocks in the file system. Episode duplicates all inodes and indirect blocks so that it can set a Copy-On-Write (COW) bit in all pointers to blocks that are used by both the active file system and the clone. In Episode, it is important to identify these blocks so that new data written to the active file system does not overwrite "old" data that is part of the done and, therefore, must not change.

Creating a clone in the prior art can use up as much as 32 MB on a 1 GB disk. The prior art requires 256 MB of disk space on a 1 GB disk (for 4 KB blocks) to keep eight clones of the file system. Thus, the prior art cannot use large numbers of clones to prevent loss of data. Instead it is used to facilitate backup of the file system onto an auxiliary storage means other than the disk drive, such as a tape backup device. Clones are used to backup a file system in a consistent state at the instant the clone is made. By cloning the file system, the done can be backed up to the auxiliary storage means without shutting down the active file system, and thereby preventing users from using the file system. Thus, clones allow users to continue accessing an active file system while the file system, in a consistent state is backed up. Then the clone is deleted once the backup is completed. Episode is not capable of supporting multiple clones since each pointer has only one COW bit. A single COW bit is not able to distinguish more than one clone. For more than one clone, there is no second COW bit that can be set.

A disadvantage of the prior art system for creating file system clones is that it involves duplicating all of the inodes and all of the indirect blocks in the file system. For a system with many small files, the inodes alone can consume a significant percentage of the total disk space in a file system. For example, a 1 GB file system that is filled with 4 KB files has 32 MB of inodes. Thus, creating an Episode done consumes a significant amount of disk space, and generates large amounts (i.e., many megabytes) of disk traffic. As a result of these conditions, creating a clone of a file system takes a significant amount of time to complete.

Another disadvantage of the prior art system is that it makes it difficult to create multiple clones of the same file system. The result of this is that clones tend to be used, one at a time, for short term operations such as backing up the file system to tape, and are then deleted.

SUMMARY OF THE INVENTION

The present invention provides a method for maintaining a file system in a consistent state and for creating read-only copies of a file system. Changes to the file system are tightly controlled to maintain the file system in a consistent state. The file system progresses from one self-consistent state to another self-consistent state. The set of self-consistent blocks on disk that is rooted by the root inode is referred to as a consistency point (CP). To implement consistency points, WAFL always writes new data to unallocated blocks on disk. It never overwrites existing data. A new consistency point occurs when the fsinfo block is updated by writing a new root inode for the inode file into it. Thus, as long as the root inode is not updated, the state of the file system represented on disk does not change.

The present invention also creates snapshots, which are virtual read-only copies of the file system. A snapshot uses no disk space when it is initially created. It is designed so that many different snapshots can be created for the same file system. Unlike prior art file systems that create a clone by duplicating the entire inode file and all of the indirect blocks, the present invention duplicates only the inode that describes the inode file. Thus, the actual disk space required for a snapshot is only the 128 bytes used to store the duplicated inode. The 128 bytes of the present invention required for a snapshot is significantly less than the many megabytes used for a clone in the prior art.

The present invention prevents new data written to the active file system from overwriting "old" data that is part of a snapshot(s). It is necessary that old data not be overwritten as long as it is part of a snapshot. This is accomplished by using a multi-bit free-block map. Most prior art file systems use a free block map having a single bit per block to indicate whether or not a block is allocated. The present invention uses a block map having 32-bit entries. A first bit indicates whether a block is used by the active file system, and 20 remaining bits are used for up to 20 snapshots, however, some bits of the 31 bits may be used for other purposes.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a prior art "clone" of a file system.

FIG. **2** is a diagram illustrating a list of inodes having dirty buffers.

FIG. **3** is a diagram illustrating an on-disk inode of WAFL.

FIGS. **4**A, **4**B, **4**C and **4**D are diagrams illustrating on-disk inodes of WAFL having different levels of indirection.

FIG. **5** is a flow diagram illustrating the method for generating a consistency point.

FIG. **6** is a flow diagram illustrating step **530** of FIG. **5** for generating a consistency point.

FIG. **7** is a flow diagram illustrating step **530** of FIG. **5** for creating a snapshot.

FIG. **8** is a diagram illustrating an incore inode of WAFL according to the present invention.

FIGS. **9**A, **9**B, **9**C, **9**D are diagrams illustrating incore inodes of WAFL having different levels of indirection according to the present invention.

FIG. **10** is a diagram illustrating an incore inode **1020** for a file.

FIGS. **11**A, **11**B, **11**C and **11**D are diagrams illustrating a block map (blkmap) file according to the present invention.

FIG. **12** is a diagram illustrating an inode file according to the present invention.

FIGS. **13**A and **13**B are diagrams illustrating an inode map (inomap) file according to the present invention.

FIG. **14** is a diagram illustrating a directory according to the present invention.

FIG. **15** is a diagram illustrating a file system information (fsinfo) structure.

FIG. **16** is a diagram illustrating the WAFL file system.

FIGS. **17**A, **17**B, **17**C, **17**D, **17**E, **17**F, **17**G, **17**H, **17**I, **17**J, **17**K and **17**L are diagrams illustrating the generation of a consistency point.

FIGS. **18**A, **18**B and **18**C are diagrams illustrating generation of a snapshot.

FIG. **19** is a diagram illustrating changes to an inode file.

FIGS. **20**A, **20**B and **20**C are diagrams illustrating fsinfo blocks used for maintaining a file system in a consistent state.

FIGS. **21**A, **21**B, **21**C, **21**D, **21**E and **21**F are detailed diagrams illustrating the generation of a snapshot.

FIG. **22** is a diagram illustrating an active WAFL file system having three snapshots that each reference a common file.

FIGS. **23**A and **23**B are diagrams illustrating the updating of atime.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

A system for creating read-only copies of a file system is described. In the following description, numerous specific details, such as number and nature of disks, disk block sizes, etc., are described in detail in order to provide a more thorough description of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without these specific details. In other instances, well-known features have not been described in detail so as not to unnecessarily obscure the present invention.

WRITE ANYWHERE FILE-SYSTEM LAYOUT

The present invention uses a Write Anywhere File-system Layout (WAFL). This disk format system is block based (i.e., 4 KB blocks that have no fragments), uses inodes to describe its files, and includes directories that are simply specially formatted files. WAFL uses files to store meta-data that describes the layout of the file system. WAFL meta-data files include: an inode file, a block map (blkmap) file, and an inode map (inomap) file. The inode file contains the inode table for the file system. The blkmap file indicates which disk blocks are allocated. The inomap file indicates which inodes are allocated. On-disk and incore WAFL inode distinctions are discussed below.

On-Disk WAFL Inodes

WAFL inodes are distinct from prior art inodes. Each on-disk WAFL inode points to 16 blocks having the same level of indirection. A block number is 4-bytes long. Use of block numbers having the same level of indirection in an inode better facilitates recursive processing of a file. FIG. **3** is a block diagram illustrating an on-disk inode **310**. The on-disk inode **310** is comprised of standard inode information **310**A and **16** block number entries **310**B having the same level of indirection. The inode information **310**A comprises information about the owner of a file, permissions, file size, access time, etc. that are well-known to a person skilled in the art. On-disk inode **310** is unlike prior art inodes that comprise a plurality of block numbers having different levels of indirection. Keeping all block number entries **310**B in an inode **310** at the same level of indirection simplifies file system implementation.

For a small file having a size of 64 bytes or less, data is stored directly in the inode itself instead of the 16 block numbers. FIG. **4**A is a diagram illustrating a Level **0** inode **410** that is similar to inode **310** shown in FIG. **3**. However, inode **410** comprises 64-bytes of data **410**B instead of **16** block numbers **310**B. Therefore, disk blocks do not need to be allocated for very small files.

For a file having a size of less than 64 KB, each of the 16 block numbers directly references a 4 KB data block. FIG. **4**B is a diagram illustrating a Level **1** inode **310** comprising 16 block numbers **310**B. The block number entries **0–15** point to corresponding 4 KB data blocks **420**A–**420**C.

For a file having a size that is greater than or equal to 64 KB and is less than 64 MB, each of the 16 block numbers references a single-indirect block. In turn, each 4 KB single-indirect block comprises **1024** block numbers that reference 4 KB data blocks. FIG. **4**C is a diagram illustrating a Level **2** inode **310** comprising 16 block numbers **310**B that reference 16 single-indirect blocks **430**A–**430**C. As shown in FIG. **4**C, block number entry **0** points to single-indirect block **430**A. Single-indirect block **430**A comprises **1024** block numbers that reference 4 KB data blocks **440**A–**440**C. Similarly, single-indirect blocks **430**B–**430**C can each address up to **1024** data blocks.

For a file size greater than 64 MB, the 16 block numbers of the inode reference double-indirect blocks. Each 4 KB double-indirect block comprises **1024** block numbers pointing to corresponding single-indirect blocks. In turn, each single-indirect block comprises **1024** block numbers that point to 4 KB data blocks. Thus, up to 64 GB can be addressed. FIG. **4**D is a diagram illustrating a Level **3** inode **310** comprising 16 block numbers **310**B wherein block number entries **0**, **1**, and **15** reference double-indirect blocks **470**A, **470**B, and **470**C, respectively. Double-indirect block **470**A comprises **1024** block number entries **0–1023** that point to **1024** single-indirect blocks **480**A–**480**B. Each single-indirect block **480**A–**480**B, in turn, references **1024** data blocks. As shown in FIG. **4**D, single-indirect block **480**A references **1024** data blocks **490**A–**490**C and single-indirect block **480**B references **1024** data blocks **490**C–**490**F.

Incore WAFL Inodes

FIG. **8** is a block diagram illustrating an incore WAFL inode **820**. The incore inode **820** comprises the information of on-disk inode **310** (shown in FIG. **3**), a WAFL buffer data structure **820**A, and 16 buffer pointers **820**B. A WAFL incore inode has a size of 300 bytes. A WAFL buffer is an incore (in memory) 4 KB equivalent of the 4 KB blocks that are stored on disk. Each incore WAFL inode **820** points to 16 buffers having the same levels of indirection. A buffer pointer is 4-bytes long. Keeping all buffer pointers **820**B in an inode **820** at the same level of indirection simplifies file system implementation. Incore inode **820** also contains incore information **820**C comprising a dirty flag, an in-consistency point (IN_CP) flag, and pointers for a linked list. The dirty flag indicates that the inode itself has been

modified or that it references buffers that have changed. The IN_CP flag is used to mark an inode as being in a consistency point (described below). The pointers for a linked list are described below.

FIG. **10** is a diagram illustrating a file referenced by a WAFL inode **1010**. The file comprises indirect WAFL buffers **1020–1024** and direct WAFL buffers **1030–1034**. The WAFL in-core inode **1010** comprises standard inode information **1010**A (including a count of dirty buffers), a WAFL buffer data structure **1010**B, 16 buffer pointers **1010**C and a standard on-disk inode **1010**D. The incore WAFL inode **1010** has a size of approximately 300 bytes. The on-disk inode is 128 bytes in size. The WAFL buffer data structure **1010**B comprises two pointers where the first one references the 16 buffer pointers **1010**C and the second references the on-disk block numbers **1010**D.

Each inode **1010** has a count of dirty buffers that it references. An inode **1010** can be put in the list of dirty inodes and/or the list of inodes that have dirty buffers. When all dirty buffers referenced by an inode are either scheduled to be written to disk or are written to disk, the count of dirty buffers of inode **1010** is set to zero. The inode **1010** is then requeued according to its flag (i.e., no dirty buffers). This inode **1010** is cleared before the next inode is processed. Further the flag of the inode indicating that it is in a consistency point is cleared. The inode **1010** itself is written to disk in a consistency point.

The WAFL buffer structure is illustrated by indirect WAFL buffer **1020**. WAFL buffer **1020** comprises a WAFL buffer data structure **1020**A, a 4 KB buffer **1020**B comprising **1024** WAFL buffer pointers and a 4 KB buffer **1020**C comprising **1024** on-disk block numbers. The WAFL buffer data structure is 56 bytes in size and comprises 2 pointers. One pointer of WAFL buffer data structure **1020**A references 4 KB buffer **1020**B and a second pointer references buffer **1020**C. In FIG. **10**, the 16 buffer pointers **1010**C of WAFL inode **1010** point to the 16 single-indirect WAFL buffers **1020–1024**. In turn, WAFL buffer **1020** references **1024** direct WAFL buffer structures **1030–1034**. WAFL buffer **1030** is representative of direct WAFL buffers.

Direct WAFL buffer **1030** comprises WAFL buffer data structure **1030**A and a 4 KB direct buffer **1030**B containing a cached version of a corresponding on-disk 4 KB data block. Direct WAFL buffer **1030** does not comprise a 4 KB buffer such as buffer **1020**C of indirect WAFL buffer **1020**. The second buffer pointer of WAFL buffer data structure **1030**A is zeroed, and therefore does not point to a second 4 KB buffer. This prevents inefficient use of memory because memory space would be assigned for an unused buffer otherwise.

In the WAFL file system as shown in FIG. **10**, a WAFL in-core inode structure **1010** references a tree of WAFL buffer structures **1020–1024** and **1030–1034**. It is similar to a tree of blocks on disk referenced by standard inodes comprising block numbers that point to indirect and/or direct blocks. Thus, WAFL inode **1010** contains not only the on-disk inode **1010**D comprising 16 volume block numbers, but also comprises 16 buffer pointers **1010**C pointing to WAFL buffer structures **1020–1024** and **1030–1034**. WAFL buffers **1030–1034** contain cached contents of blocks referenced by volume block numbers.

The WAFL incore inode **1010** contains 16 buffer pointers **1010**C. In turn, the 16 buffer pointers **1010**C are referenced by a WAFL buffer structure **1010**B that roots the tree of WAFL buffers **1020–1024** and **1030–1034**. Thus, each WAFL inode **1010** contains a WAFL buffer structure **1010**B that points to the 16 buffer pointers **1010**C in the inode **1010**. This facilitates algorithms for handling trees of buffers that are implemented recursively. If the 16 buffer pointers **1010**C in the inode **1010** were not represented by a WAFL buffer structure **1010**B, the recursive algorithms for operating on an entire tree of buffers **1020–1024** and **1030–1034** would be difficult to implement.

FIGS. **9**A–**9**D are diagrams illustrating inodes having different levels of indirection. In FIGS. **9**A–**9**D, simplified indirect and direct WAFL buffers are illustrated to show indirection. However, it should be understood that the WAFL buffers of FIG. **9** represent corresponding indirect and direct buffers of FIG. **10**. For a small file having a size of 64 bytes or less, data is stored directly in the inode itself instead of the 16 buffer pointers. FIG. **9**A is a diagram illustrating a Level **0** inode **820** that is the same as inode **820** shown in FIG. **8** except that inode **820** comprises 64-bytes of data **920**B instead of 16 buffer pointers **820**B. Therefore, additional buffers are not allocated for very small files.

For a file having a size of less than **64** KB, each of the 16 buffer pointers directly references a 4 KB direct WAFL buffer. FIG. **9**B is a diagram illustrating a Level **1** inode **820** comprising 16 buffer pointers **820**B. The buffer pointers PTR**0**–PTR**15** point to corresponding 4 KB direct WAFL buffers **922**A–**922**C.

For a file having a size that is greater than or equal to 64 KB and is less than 64 MB, each of the 16 buffer pointers references a single-indirect WAFL buffer. In turn, each 4 KB single-indirect WAFL buffer comprises **1024** buffer pointers that reference 4 KB direct WAFL buffers. FIG. **9**C is a diagram illustrating a Level **2** inode **820** comprising 16 buffer pointers **820**B that reference 16 single-indirect WAFL buffers **930**A–**930**C. As shown in FIG. **9**C, buffer pointer PTR**0** points to single-indirect WAFL buffer **930**A. Single-indirect WAFL buffer **930**A comprises **1024** pointers that reference 4 KB direct WAFL buffers **940**A–**940**C. Similarly, single-indirect WAFL buffers **930**B–**930**C can each address up to **1024** direct WAFL buffers.

For a file size greater than 64 MB, the 16 buffer pointers of the inode reference double-indirect WAFL buffers. Each 4 KB double-indirect WAFL buffer comprises **1024** pointers pointing to corresponding single-indirect WAFL buffers. In turn, each single-indirect WAFL buffer comprises **1024** pointers that point to 4 KB direct WAFL buffers. Thus, up to 64 GB can be addressed. FIG. **9**D is a diagram illustrating a Level **3** inode **820** comprising 16 pointers **820**B wherein pointers PTR**0**, PTR**1**, and PTR**15** reference double-indirect WAFL buffers **970**A, **970**B, and **970**C, respectively. Double-indirect WAFL buffer **970**A comprises **1024** pointers that point to **1024** single-indirect WAFL buffers **980**A–**980**B. Each single-indirect WAFL buffer **980**A–**980**B, in turn, references **1024** direct WAFL buffers. As shown in FIG. 9D, single-indirect WAFL buffer **980**A references **1024** direct WAFL buffers **990**A–**990**C and single-indirect WAFL buffer **980**B references **1024** direct WAFL buffers **990**D–**990**F.

Directories

Directories in the WAFL system are stored in 4 KB blocks that are divided into two sections. FIG. **14** is a diagram illustrating a directory block **1410** according to the present invention. Each directory block **1410** comprises a first section **1410**A comprising fixed length directory entry structures **1412–1414** and a second section **1410**B containing the actual directory names **1416–1418**. Each directory entry also contains a file id and a generation. This information identifies what file the entry references. This information is well-known in the art, and therefore is not illustrated in FIG.

14. Each entry **1412–1414** in the first section **1410**A of the directory block has a pointer to its name in the second section **1410**B. Further, each entry **1412–1414** includes a hash value dependent upon its name in the second section **1410**B so that the name is examined only when a hash hit (a hash match) occurs. For example, entry **1412** of the first section **1410**A comprises a hash value **1412**A and a pointer **1412**B. The hash value **1412**A is a value dependent upon the directory name "DIRECTORY_ABC" stored in variable length entry **1416** of the second section **1410**B. Pointer **1412**B of entry **1410** points to the variable length entry **1416** of second section **1410**B. Using fixed length directory entries **1412–1414** in the first section **1410**A speeds up the process of name lookup. A calculation is not required to find the next entry in a directory block **1410**. Further, keeping entries **1412–1414** in the first section small **1410**A improves the hit rate for file systems with a line-fill data cache.

Meta-Data

WAFL keeps information that describes a file system in files known as meta-data. Meta-data comprises an inode file, inomap file, and a blkmap file. WAFL stores its meta-data in files that may be written anywhere on a disk. Because all WAFL meta-data is kept in files, it can be written to any location just like any other file in the file system.

A first meta-data file is the "inode file" that contains inodes describing all other files in the file system. FIG. **12** is a diagram illustrating an inode file **1210**. The inode file **1210** may be written anywhere on a disk unlike prior art systems that write "inode tables" to a fixed location on disk. The inode file **1210** contains an inode **1210**A–**1210**F for each file in the file system except for the inode file **1210** itself. The inode file **1210** is pointed to by an inode referred to as the "root inode". The root inode is kept in a fixed location on disk referred to as the file system information (fsinfo) block described below. The inode file **1210** itself is stored in 4 KB blocks on disk (or 4 KB buffers in memory). FIG. **12** illustrates that inodes **1210**A–**1210**C are stored in a 4 KB buffer **1220**. For on-disk inode sizes of 128 bytes, a 4 KB buffer (or block) comprises 32 inodes. The incore inode file **1210** is composed of WAFL buffers **1220**. When an incore inode (i.e., **820**) is loaded, the on-disk inode part of the incore inode **820** is copied from the buffer **1220** of the inode file **1210**. The buffer data itself is loaded from disk. Writing data to disk is done in the reverse order. The incore inode **820**, which contains a copy of the ondisk inode, is copied to the corresponding buffer **1220** of the inode file **1210**. Then, the inode file **1210** is write-allocated, and the data stored in the buffer **1220** of the inode file **1210** is written to disk.

Another meta-data file is the "block map" (blkmap) file. FIG. **11**A is a diagram illustrating a blkmap file **1110**. The blkmap file **1110** contains a 32-bit entry **1110**A–**1110**D for each 4 KB block in the disk system. It also serves as a free-block map file. The blkmap file **1110** indicates whether or not a disk block has been allocated. FIG. **11**B is a diagram of a block entry **1110**A of blkmap file **1110** (shown in FIG. **11**A). As shown in FIG. **11**B, entry **1110**A is comprised of 32 bits (BIT**0**–BIT**31**). Bit **0** (BIT**0**) of entry **1110**A is the active file system bit (FS-BIT). The FS-bit of entry **1110**A indicates whether or not the corresponding block is part of the active file system. Bits **1–20** (BIT**1**–BIT**20**) of entry **1110**A are bits that indicate whether the block is part of a corresponding snapshot **1–20**. The next upper 10 bits (BIT**21**–BIT**30**) are reserved. Bit **31** (BIT**31**) is the consistency point bit (CP-BIT) of entry **1110**A.

A block is available as a free block in the file system when all bits (BIT**0**–BIT**31**) in the 32-bit entry **1110**A for the block

are clear (reset to a value of 0). FIG. **11**C is a diagram illustrating entry **1110**A of FIG. **11**A indicating the disk block is free. Thus, the block referenced by entry **1110**A of blkmap file **1110** is free when bits **0–31** (BIT**0**–BIT**31**) all have values of 0. FIG. **11**D is a diagram illustrating entry **1110**A of FIG. **11**A indicating an allocated block in the active file system. When bit **0** (BIT**0**), also referred to as the FS-bit, is set to a value of 1, the entry **1110**A of blkmap file **1110** indicates a block that is part of the active file system. Bits **1–20** (BIT**1**–BIT**20**) are used to indicate corresponding snapshots, if any, that reference the block. Snapshots are described in detail below. If bit **0** (BIT**0**) is set to a value of 0, this does not necessarily indicate that the block is available for allocation. All the snapshot bits must also be zero for the block to be allocated. Bit **31** (BIT**31**) of entry **1110**A always has the same state as bit **0** (BIT**0**) on disk, however, when loaded into memory bit **31** (BIT**31**) is used for bookkeeping as part of a consistency point.

Another meta-data file is the "inode map" (inomap) file that serves as a free inode map. FIG. **13**A is a diagram illustrating an inomap file **1310**. The inomap file **1310** contains an 8-bit entry **1310**A–**1310**C for each block in the inode file **1210** shown in FIG. **12**. Each entry **1310**A–**1310**C is a count of allocated inodes in the corresponding block of the inode file **1210**. FIG. **13**A shows values of 32, 5, and 0 in entries **1310**A–**1310**C, respectively. The inode file **1210** must still be inspected to find which inodes in the block are free, but does not require large numbers of random blocks to be loaded into memory from disk. Since each 4 KB block **1220** of inode file **1210** holds 32 inodes, the 8-bit inomap entry **1310**A–**1310**C for each block of inode file **1210** can have values ranging from 0 to 32. When a block **1220** of an inode file **1210** has no inodes in use, the entry **1310**A–**1310**C for it in inomap file **1310** is 0. When all the inodes in the block **1220** inode file **1210** are in use, the entry **1310**A–**1310**C of the inomap file **1310** has a value of 32.

FIG. **13**B is a diagram illustrating an inomap file **1350** that references the 4 KB blocks **1340**A–**1340**C of inode file **1340**. For example, inode file **1340** stores 37 inodes in three 4 KB blocks **1340**A–**1340**C. Blocks **1340**A–**1340**C of inode file **1340** contain 32, 5, and 0 used inodes, respectively. Entries **1350**A–**1350**C of blkmap file **1350** reference blocks **1340**A–**1340**C of inode file **1340**, respectively. Thus, the entries **1350**A–**1350**C of inomap file have values of 32, 5, and 0 for blocks **1340**A–**1340**C of inode file **1340**. In turn, entries **1350**A–**1350**C of inomap file indicate 0, 27, and 32 free inodes in blocks **1340**A–**1340**C of inode file **1340**, respectively.

Referring to FIGS. **13**A and **13**B using a bitmap for the entries **1310**A–**1310**C of inomap file **1310** instead of counts is disadvantageous since it would require 4 bytes per entry **1310**A–**1310**C for block **1220** of the inode file **1210** (shown in FIG. **12**) instead of one byte. Free inodes in the block(s) **1220** of the inode file **1210** do not need to be indicated in the inomap file **1310** because the inodes themselves contain that information.

FIG. **15** is a diagram illustrating a file system information (fsinfo) structure **1510**. The root inode **1510**B of a file system is kept in a fixed location on disk so that it can be located during booting of the file system. File system information structure **1510** is not a meta-data file but is part of the WAFL system. The root inode **1510**B is an inode referencing the inode file **1210**. It is part of the file system information (fsinfo) structure **1510** that also contains information **1510**A including the number of blocks in the file system, the creation time of the file system, etc. The miscellaneous information **1510**A further comprises a check-

sum **1510**C (described below). Except for the root inode **1510**B itself, this information **1510**A can be kept in a meta-data file in an alternate embodiment. Two identical copies of the fsinfo structure **1510** are kept in fixed locations on disk.

FIG. **16** is a diagram illustrating the WAFL file system **1670** in a consistent state on disk comprising two fsinfo blocks **1610** and **1612**, inode file **1620**, blkmap file **1630**, inomap file **1640**, root directory **1650**, and a typical file (or directory) **1660**. Inode file **1620** is comprised of a plurality of inodes **1620**A–**1620**D that reference other files **1630**–**1660** in the file system **1670**. Inode **1620**A of inode file **1620** references blkmap file **1630**. Inode **1620**B references inomap file **1640**. Inode **1620**C references root directory **1650**. Inode **1620**D references a typical file (or directory) **1660**. Thus, the inode file points to all files **1630**–**1660** in the file system **1670** except for fsinfo blocks **1610** and **1612**. Fsinfo blocks **1610** and **1612** each contain a copy **1610**B and **1612**B of the inode of the inode file **1620**, respectively. Because the root inode **1610**B and **1612**B of fsinfo blocks **1610** and **1612** describes the inode file **1620**, which in turn describes the rest of the files **1630**–**1660** in the file system **1670** including all meta-data files **1630**–**1640**, the root inode **1610**B and **1612**B is viewed as the root of a tree of blocks. The WAFL system **1670** uses this tree structure for its update method (consistency point) and for implementing snapshots, both described below.

List of Inodes Having Dirty Blocks

WAFL in-core inodes (i.e., WAFL inode **1010** shown in FIG. **10**) of the WAFL file system are maintained in different linked lists according to their status. Inodes that reference dirty blocks are kept in a dirty inode list as shown in FIG. **2**. Inodes containing valid data that is not dirty are kept in a separate list and inodes that have no valid data are kept in yet another, as is well-known in the art. The present invention utilizes a list of inodes having dirty data blocks that facilitates finding all of the inodes that need write allocations to be done.

FIG. **2** is a diagram illustrating a list **210** of dirty inodes according to the present invention. The list **210** of dirty inodes comprises WAFL in-core inodes **220**–**250**. As shown in FIG. **2**, each WAFL in-core inode **220**–**250** comprises a pointer **220**A–**250**A, respectively, that points to another inode in the linked list. For example, WAFL inodes **220**–**250** are stored in memory at locations **2048**, **2152**, **2878**, **3448** and **3712**, respectively. Thus, pointer **220**A of inode **220** contains address **2152**. It points therefore to WAFL inode **222**. In turn, WAFL inode **222** points to WAFL inode **230** using address **2878**. WAFL inode **230** points to WAFL inode **240**. WAFL inode **240** points to inode **250**. The pointer **250**A of WAFL inode **250** contains a null value and therefore does not point to another inode. Thus, it is the last inode in the list **210** of dirty inodes. Each inode in the list **210** represents a file comprising a tree of buffers as depicted in FIG. **10**. At least one of the buffers referenced by each inode **220**–**250** is a dirty buffer. A dirty buffer contains modified data that must be written to a new disk location in the WAFL system. WAFL always writes dirty buffers to new locations on disk.

CONSISTENCY POINTS

The WAFL disk structure described so far is static. In the present invention, changes to the file system **1670** are tightly controlled to maintain the file system **1670** in a consistent state. The file system **1670** progresses from one self-consistent state to another self-consistent state. The set (or tree) of self-consistent blocks on disk that is rooted by the

root inode **1510**B is referred to as a consistency point (CP). To implement consistency points, WAFL always writes new data to unallocated blocks on disk. It never overwrites existing data. Thus, as long as the root inode **1510**B is not updated, the state of the file system **1670** represented on disk does not change. However, for a file system **1670** to be useful, it must eventually refer to newly written data, therefore a new consistency point must be written.

Referring to FIG. **16**, a new consistency point is written by first flushing all file system blocks to new locations on disk (including the blocks in meta-data files such as the inode file **1620**, blkmap file **1630**, and inomap file **1640**). A new root inode **1610**B and **1612**B for the file system **1670** is then written to disk. With this method for atomically updating a file system, the on-disk file system is never inconsistent. The on-disk file system **1670** reflects an old consistency point up until the root inode **1610**B and **1612**B is written. Immediately after the root inode **1610**B and **1612**B is written to disk, the file system **1670** reflects a new consistency point. Data structures of the file system **1670** can be updated in any order, and there are no ordering constraints on disk writes except the one requirement that all blocks in the file system **1670** must be written to disk before the root inode **1610**B and **1612**B is updated.

To convert to a new consistency point, the root inode **1610**B and **1612**B must be updated reliably and atomically. WAFL does this by keeping two identical copies of the fsinfo structure **1610** and **1612** containing the root inode **1610**B and **1612**B. During updating of the root inode **1610**B and **1612**B, a first copy of the fsinfo structure **1610** is written to disk, and then the second copy of the fsinfo structure **1612** is written. A checksum **1610**C and **1612**C in the fsinfo structure **1610** and **1612**, respectively, is used to detect the occurrence of a system crash that corrupts one of the copies of the fsinfo structure **1610** or **1612**, each containing a copy of the root mode, as it is being written to disk. Normally, the two fsinfo structures **1610** and **1612** are identical.

Algorithm for Generating a Consistency Point

FIG. **5** is a diagram illustrating the method of producing a consistency point. In step **510**, all "dirty" inodes (inodes that point to new blocks containing modified data) in the system are marked as being in the consistency point. Their contents, and only their contents, are written to disk. Only when those writes are complete are any writes from other inodes allowed to reach disk. Further, during the time dirty writes are occurring, no new modifications can be made to inodes that have their consistency point flag set

In addition to setting the consistency point flag for all dirty inodes that are part of the consistency point, a global consistency point flag is set so that user-requested changes behave in a tightly controlled manner. Once the global consistency point flag is set, user-requested changes are not allowed to affect inodes that have their consistency point flag set. Further, only inodes having a consistency point flag that is set are allocated disk space for their dirty blocks. Consequently, the state of the file system will be flushed to disk exactly as it was when the consistency point began.

In step **520**, regular files are flushed to disk. Flushing regular files comprises the steps of allocating disk space for dirty blocks in the regular files, and writing the corresponding WAFL buffers to disk. The inodes themselves are then flushed (copied) to the inode file. All inodes that need to be written are in either the list of inodes having dirty buffers or the list of inodes that are dirty but do not have dirty buffers. When step **520** is completed, there are no more ordinary inodes with the consistency point flag set, and all incoming

I/O requests succeed unless the requests use buffers that are still locked up for disk I/O operations.

In step **530**, special files are flushed to disk. Flushing special files comprises the steps of allocating disk space for dirty blocks in the two special files (the inode file and the blkmap file), updating the consistency bit (CP-bit) to match the active file system bit (FS-bit) for each entry in the blkmap file, and then writing the blocks to disk. Write allocating the inode file and the blkmap is complicated because the process of write allocating them changes the files themselves. Thus, in step **530** writes are disabled while changing these files to prevent important blocks from locking up in disk I/O operations before the changes are completed.

Also, in step **530**, the creation and deletion of snapshots, described below, are performed because it is the only point in time when the file system, except for the fsinfo block, is completely self consistent and about to be written to disk. A snapshot is deleted from the file system before a new one is created so that the same snapshot inode can be used in one pass.

FIG. **6** is a flow diagram illustrating the steps that step **530** comprises. Step **530** allocates disk space for the blkmap file and the inode file and copies the active FS-bit into the CP-bit for each entry in the blkmap file. In step **610**, the inode for the blkmap file is pre-flushed to the inode file. This ensures that the block in the inode file that contains the inode of the blkmap file is dirty so that step **620** allocates disk space for it.

In step **620**, disk space is allocated for all dirty blocks in the inode and blkmap files. The dirty blocks include the block in the inode file containing the inode of the blkmap file.

In step **630**, the inode for the blkmap file is flushed again, however this time the actual inode is written to the pre-flushed block in the inode file. Step **610** has already dirtied the block of the inode file that contains the inode of the blkmap file. Thus, another write-allocate, as in step **620**, does not need to be scheduled.

In step **640**, the entries for each block in the blkmap file are updated. Each entry is updated by copying the active FS-bit to the CP-bit (i.e., copying bit **0** into bit **31**) for all entries in dirty blocks in the blkmap file.

In step **650**, all dirty blocks in the blkmap and inode files are written to disk.

Only entries in dirty blocks of the blkmap file need to have the active file system bit (FS-bit) copied to the consistency point bit (CP-bit) in step **640**. Immediately after a consistency point, all blkmap entries have the same value for both the active FS-bit and CP-bit. As time progresses, some active FS-bits of blkmap file entries for the file system are either cleared or set. The blocks of the blkmap file containing the changed FS-bits are accordingly marked dirty. During the following consistency point, blocks that are clean do not need to be re-copied. The clean blocks are not copied because they were not dirty at the previous consistency point and nothing in the blocks has changed since then. Thus, as long as the file system is initially created with the active FS-bit and the CP-bit having the same value in all blkmap entries, only entries with dirty blocks need to be updated at each consistency point.

Referring to FIG. **5**, in step **540**, the file system information (fsinfo) block is first updated and then flushed to disk. The fsinfo block is updated by writing a new root inode for the inode file into it. The fsinfo block is written twice. It is first written to one location and then to a second location. The two writes are performed so that when a system crash occurs during either write, a self-consistent file system exists on disk. Therefore, either the new consistency point is available if the system crashed while writing the second fsinfo block or the previous consistency point (on disk before the recent consistency point began) is available if the first fsinfo block failed. When the file system is restarted after a system failure, the highest generation count for a consistency point in the fsinfo blocks having a correct checksum value is used. This is described in detail below.

In step **550**, the consistency point is completed. This requires that any dirty inodes that were delayed because they were not part of the consistency point be requeued. Any inodes that had their state change during the consistency point are in the consistency point wait (CP_WAIT) queue. The CP_WAIT queue holds inodes that changed before step **540** completed, but after step **510** when the consistency point started. Once the consistency point is completed, the inodes in the CP_WAIT queue are re-queued accordingly in the regular list of inodes with dirty buffers and list of dirty inodes without dirty buffers.

Single Ordering Constraint of Consistency Point

The present invention, as illustrated in FIGS. **20**A–**20**C, has a single ordering constraint. The single ordering constraint is that the fsinfo block **1810** is written to disk only after all the other blocks are written to disk. The writing of the fsinfo block **1810** is atomic, otherwise the entire file system **1830** could be lost. Thus, the WAFL file system requires the fsinfo block **1810** to be written at once and not be in an inconsistent state. As illustrated in FIG. **15**, each of the fsinfo blocks **1510** contains a checksum **1510**C and a generation count **1510**D.

FIG. **20**A illustrates the updating of the generation count **1810**D and **1870**D of fsinfo blocks **1810** and **1870**. Each time a consistency point (or snapshot) is performed, the generation count of the fsinfo block is updated. FIG. **20**A illustrates two fsinfo blocks **1810** and **1870** having generation counts **1810**D and **1870**D, respectively, that have the same value of N indicating a consistency point for the file system. Both fsinfo blocks reference the previous consistency point (old file system on disk) **1830**. A new version of the file system exists on disk and is referred to as new consistency point **1831**. The generation count is incremented every consistency point.

In FIG. **20**B, the generation count **1810**D of the first fsinfo block **1810** is updated and given a value of N+1. It is then written to disk. FIG. **20**B illustrates a value of N+1 for generation count **1810**D of fsinfo block **1810** whereas the generation count **1870**D of the second fsinfo block **1870** has a value of N. Fsinfo block **1810** references new consistency point **1831** whereas fsinfo block **1870** references old consistency point **1830**. Next, the generation count **1870**D of fsinfo block **1870** is updated and written to disk as illustrated in FIG. **20**C. In FIG. **20**C, the generation count **1870**D of fsinfo block **1870** has a value of N+1. Therefore the two fsinfo blocks **1810** and **1870** have the same generation count value of N+1.

When a system crash occurs between fsinfo block updates, each copy of the fsinfo block **1810** and **1870** has a self consistent checksum (not shown in the diagram), but one of the generation numbers **1810**D or **1870**D has a higher value. That is, a system crash occurs when the file system is in the state illustrated in FIG. **20**B. For example, in the preferred embodiment of the present invention as illustrated in FIG. **20**B, the generation count **1810**D of fsinfo block **1810** is updated before the second fsinfo block **1870**.

Therefore, the generation count **1810**D (value of N+1) is greater than the generation count **1870**(value of N)D of fsinfo block **1870**. Because the generation count of the first fsinfo block **1810** is higher, it is selected for recovering the file system after a system crash. This is done because the first fsinfo block **1810** contains more current data as indicated by its generation count **1810**D. For the case when the first fsinfo block is corrupted because the system crashes while it is being updated, the other copy **1870** of the fsinfo block is used to recover the file system **1830** into a consistent state.

It is not possible for both fsinfo blocks **1810** and **1870** to be updated at the same time in the present invention. Therefore, at least one good copy of the fsinfo block **1810** and **1870** exists in the file system. This allows the file system to always be recovered into a consistent state.

WAFL does not require special recovery procedures. This is unlike prior art systems that use logging, ordered writes, and mostly ordered writes with recovery. This is because only data corruption, which RAID protects against, or software can corrupt a WAFL file system. To avoid losing data when the system fails, WAFL may keep a non-volatile transaction log of all operations that have occurred since the most recent consistency point. This log is completely independent of the WAFL disk format and is required only to prevent operations from being lost during a system crash. However, it is not required to maintain consistency of the file system.

Generating A Consistency Point

As described above, changes to the WAFL file system are tightly controlled to maintain the file system in a consistent state. FIGS. **17**A–**17**L illustrate the generation of a consistency point for a WAFL file system. The generation of a consistency point is described with reference to FIGS. **5** and **6**.

In FIGS. **17**A–**17**L, buffers that have not been modified do not have asterisks beside them. Therefore, these buffers contain the same data as corresponding on-disk blocks. Thus, a block may be loaded into memory but it has not changed with respect to its on disk version. A buffer with a single asterisk (*) beside it indicates a dirty buffer in memory (its data is modified). A buffer with a double asterisk (**) beside it indicates a dirty buffer that has been allocated disk space. Finally, a buffer with a triple asterisk (***) is a dirty buffer that is written into a new block on disk. This convention for denoting the state of buffers is also used with respect to FIGS. **21**A–**21**E.

FIG. **17**A illustrates a list **2390** of inodes with dirty buffers comprising inodes **2306**A and **2306**B. Inodes **2306**A and **2306**B reference trees of buffers where at least one buffer of each tree has been modified. Initially, the consistency point flags **2391** and **2392** of inodes **2306**A and **2306**B are cleared (**0**). While a list **2390** of inodes with dirty buffers is illustrated for the present system, it should be apparent to a person skilled in the art that other lists of inodes may exist in memory. For instance, a list of inodes that are dirty but do not have dirty buffers is maintained in memory. These inodes must also be marked as being in the consistency point. They must be flushed to disk also to write the dirty contents of the inode file to disk even though the dirty inodes do not reference dirty blocks. This is done in step **520** of FIG. **5**.

FIG. **17**B is a diagram illustrating a WAFL file system of a previous consistency point comprising fsinfo block **2302**, inode file **2346**, blkmap file **2344** and files **2340** and **2342**. File **2340** comprises blocks **2310**–**2314** containing data "A", "B", and "C", respectively. File **2342** comprises data blocks **2316**–**2320** comprising data "D", "E", and "F", respectively.

Blkmap file **2344** comprises block **2324**. The inode file **2346** comprises two 4 KB blocks **2304** and **2306**. The second block **2306** comprises inodes **2306**A–**2306**C that reference file **2340**, file **2342**, and blkmap file **2344**, respectively. This is illustrated in block **2306** by listing the file number in the inode. Fsinfo block **2302** comprises the root inode. The root inode references blocks **2304** and **2306** of inode file **2346**. Thus, FIG. **17**B illustrates a tree of buffers in a file system rooted by the fsinfo block **2302** containing the root inode.

FIG. **17**C is a diagram illustrating two modified buffers for blocks **2314** and **2322** in memory. The active file system is modified so that the block **2314** containing data "C" is deleted from file **2340**. Also, the data "F" stored in block **2320** is modified to "F-prime", and is stored in a buffer for disk block **2322**. It should be understood that the modified data contained in buffers for disk blocks **2314** and **2322** exists only in memory at this time. All other blocks in the active file system in FIG. **17**C are not modified, and therefore have no asterisks beside them. However, some or all of these blocks may have corresponding clean buffers in memory.

FIG. **17**D is a diagram illustrating the entries **2324**A–**2324**M of the blkmap file **2344** in memory. Entries **2324**A–**2324**M are contained in a buffer for 4 KB block **2324** of blkmap file **2344**. As described previously, BIT**0** and BIT**31** are the FS-BIT and CP-BIT, respectively. The consistency point bit (CP-BIT) is set during a consistency point to ensure that the corresponding block is not modified once a consistency point has begun, but not finished. BIT**1** is the first snapshot bit (described below). Blkmap entries **2324**A and **2324**B illustrate that, as shown in FIG. **17**B, the 4 KB blocks **2304** and **2306** of inode file **2346** are in the active file system (FS-BIT equal to 1) and in the consistency point (CP-BIT equal to 1). Similarly, the other blocks **2310**–**2312** and **2316**–**2320** and **2324** are in the active file system and in the consistency point. However, blocks **2308**, **2322**, and **2326**–**2328** are neither in the active file system nor in the consistency point (as indicated by BIT**0** and BIT**31**, respectively). The entry for deleted block **2314** has a value of 0 in the FS-BIT indicating that it has been removed from the active file system.

In step **510** of FIG. **5**, all "dirty" inodes in the system are marked as being in the consistency point. Dirty inodes include both inodes that are dirty and inodes that reference dirty buffers. FIG. **17**I illustrates a list of inodes with dirty buffers where the consistency point flags **2391** and **2392** of inodes **2306**A and **2306**B are set (1). Inode **2306**A references block **2314** containing data "C" of file **2340** which is to be deleted from the active file system. Inode **2306**B of block **2306** of inode file **2346** references file **2342**. Block **2320** containing data "Fprime" has been modified and a new block containing data "F" must be allocated. This is illustrated in FIG. **17**E.

In step **520**, regular files are flushed to disk. Thus, block **2322** is allocated disk space. Block **2314** of file **2340** is to be deleted, therefore nothing occurs to this block until the consistency point is subsequently completed. Block **2322** is written to disk in step **520**. This is illustrated in FIG. **17**F where buffers for blocks **2322** and **2314** have been written to disk (marked by ***). The intermediate allocation of disk space (**) is not shown. The incore copies of inodes **2308**A and **2308**B of block **2308** of inode file **2346** are copied to the inode file. The modified data exists in memory only, and the buffer **2308** is marked dirty. The consistency point flags **2391** and **2392** of inodes **2306**A and **2306**B are then cleared (0) as illustrated in FIG. **17**A. This releases the inodes for use by other processes. Inode **2308**A of block **2308** refer-

ences blocks **2310** and **2312** of file **2346**. Inode **2308**B references blocks **2316**, **2318**, and **2322** for file **2342**. As illustrated in FIG. **17**F, disk space is allocated for direct block **2322** for file **2342** and that block is written to disk. However, the file system itself has not been updated. Thus, the file system remains in a consistent state.

In step **530**, the blkmap file **2344** is flushed to disk. This is illustrated in FIG. **17**G where the blkmap file **2344** is indicated as being dirty by the asterisk.

In step **610** of FIG. **6**, the inode for the blkmap file is pre-flushed to the inode file as illustrated in FIG. **17**H. Inode **2308**C has been flushed to block **2308** of inode file **2346**. However, inode **2308**C still references block **2324**. In step **620**, disk space is allocated for blkmap file **2344** and inode file **2346**. Block **2308** is allocated for inode file **2346** and block **2326** is allocated for blkmap file **2344**. As described above, block **2308** of inode file **2346** contains a pre-flushed inode **2308**C for blkmap file **2344**. In step **630**, the inode for the blkmap file **2344** is written to the pre-flushed block **2308**C in inode file **2346**. Thus, incore inode **2308**C is updated to reference block **2326** in step **620**, and is copied into the buffer in memory containing block **2306** that is to be written to block **2308**. This is illustrated in FIG. **17**H where inode **2308**C references block **2326**.

In step **640**, the entries **2326**A–**2326**L for each block **2304**–**2326** in the blkmap file **2344** are updated in FIG. **17**J. Blocks that have not changed since the consistency point began in FIG. **17**B have the same values in their entries. The entries are updated by copying BIT**0** (FS-bit) to the consistency point bit (BIT**31**). Block **2306** is not part of the active file system, therefore BIT**0** is equal to zero (BIT**0** was turned off in step **620** when block **2308** was allocated to hold the new data for that part of the inode file). This is illustrated in FIG. **17**J for entry **2326**B. Similarly, entry **2326**F for block **2314** of file **2340** has BIT**0** and BIT**31** equal to zero. Block **2320** of file **2342** and block **2324** of blkmap file **2344** are handled similarly as shown in entries **2362**I and **2326**K, respectively. In step **650**, dirty block **2308** of inode file **2346** and dirty block **2326** of blkmap file **2344** are written to disk. This is indicated in FIG. **17**K by a triple asterisk (***) beside blocks **2308** and **2326**.

Referring to FIG. **5**, in step **540**, the file system information block **2302** is flushed to disk; this is performed twice. Thus, fsinfo block **2302** is dirtied and then written to disk (indicated by a triple asterisk) in FIG. **17**L. In FIG. **17**L, a single fsinfo block **2302** is illustrated. As shown in the diagram, fsinfo block **2302** now references block **2304** and **2308** of the inode file **2346**. In FIG. **17**L, block **2306** is no longer part of the inode file **2346** in the active file system. Similarly, file **2340** referenced by inode **2308**A of inode file **2346** comprises blocks **2310** and **2312**. Block **2314** is no longer part of file **2340** in this consistency point. File **2342** comprises blocks **2316**, **2318**, and **2322** in the new consistency point whereas block **2320** is not part of file **2342**. Further, block **2308** of inode file **2346** references a new blkmap file **2344** comprising block **2326**.

As shown in FIG. **17**L, in a consistency point, the active file system is updated by copying the inode of the inode file **2346** into fsinfo block **2302**. However, the blocks **2314**, **2320**, **2324**, and **2306** of the previous consistency point remain on disk. These blocks are never overwritten when updating the file system to ensure that both the old consistency point **1830** and the new consistency point **1831** exist on disk in FIG. **20** during step **540**

SNAPSHOTS

The WAFL system supports snapshots. A snapshot is a read-only copy of an entire file system at a given instant when the snapshot is created. A newly created snapshot refers to exactly the same disk blocks as the active file system does. Therefore, it is created in a small period of time and does not consume any additional disk space. Only as data blocks in the active file system are modified and written to new locations on disk does the snapshot begin to consume extra space.

WAFL supports up to 20 different snapshots that are numbered 1 through 20. Thus, WAFL allows the creation of multiple "clones" of the same file system. Each snapshot is represented by a snapshot inode that is similar to the representation of the active file system by a root inode. Snapshots are created by duplicating the root data structure of the file system. In the preferred embodiment, the root data structure is the root inode. However, any data structure representative of an entire file system could be used. The snapshot inodes reside in a fixed location in the inode file. The limit of 20 snapshots is imposed by the size of the blkmap entries. WAFL requires two steps to create a new snapshot N: copy the root inode into the inode for snapshot N; and, copy bit **0** into bit N of each blkmap entry in the blkmap file. Bit **0** indicates the blocks that are referenced by the tree beneath the root inode.

The result is a new file system tree rooted by snapshot inode N that references exactly the same disk blocks as the root inode. Setting a corresponding bit in the blkmap for each block in the snapshot prevents snapshot blocks from being freed even if the active file system no longer uses the snapshot blocks. Because WAFL always writes new data to unused disk locations, the snapshot tree does not change even though the active file system changes. Because a newly created snapshot tree references exactly the same blocks as the root inode, it consumes no additional disk space. Over time, the snapshot references disk blocks that would otherwise have been freed. Thus, over time the snapshot and the active file system share fewer and fewer blocks, and the space consumed by the snapshot increases. Snapshots can be deleted when they consume unacceptable numbers of disk blocks.

The list of active snapshots along with the names of the snapshots is stored in a meta-data file called the snapshot directory. The disk state is updated as described above. As with all other changes, the update occurs by automatically advancing from one consistency point to another. Modified blocks are written to unused locations on the disk after which a new root node describing the updated file system is written.

Overview of Snapshots

FIG. **18**A is a diagram of the file system **1830**, before a snapshot is taken, where levels of indirection have been removed to provide a simpler overview of the WAFL file system. The file system **1830** represents the file system **1690** of FIG. **16**. The file system **1830** is comprised of blocks **1812**–**1820**. The inode of the inode file is contained in fsinfo block **1810**. While a single copy of the fsinfo block **1810** is shown in FIG. **18**A, it should be understood that a second copy of fsinfo block exists on disk. The inode **1810**A contained in the fsinfo block **1810** comprises **16** pointers that point to **16** blocks having the same level of indirection. The blocks **1812**–**1820** in FIG. **18**A represent all blocks in the file system **1830** including direct blocks, indirect blocks, etc. Though only five blocks **1812**–**1820** are shown, each block may point to other blocks.

FIG. **18**B is a diagram illustrating the creation of a snapshot. The snapshot is made for the entire file system **1830** by simply copying the inode **1810**A of the inode file

that is stored in fsinfo block **1810** into the snapshot inode **1822**. By copying the inode **1810**A of the inode file, a new file of inodes is created representing the same file system as the active file system. Because the inode **1810**A of the inode file itself is copied, no other blocks **1812–1820** need to be duplicated. The copied inode or snapshot inode **1822**, is then copied into the inode file, which dirties a block in the inode file. For an inode file comprised of one or more levels of indirection, each indirect block is in turn dirtied. This process of dirtying blocks propagates through all the levels of indirection. Each 4 KB block in the inode file on disk contains 32 inodes where each inode is 128 bytes long.

The new snapshot inode **1822** of FIG. **18**B points back to the highest level of indirection blocks **1812–1820** referenced by the inode **1810**A of the inode file when the snapshot **1822** was taken. The inode file itself is a recursive structure because it contains snapshots of the file system **1830**. Each snapshot **1822** is a copy of the inode **1810**A of the inode file that is copied into the inode file.

FIG. **18**C is a diagram illustrating the active file system **1830** and a snapshot **1822** when a change to the active file system **1830** subsequently occurs after the snapshot **1822** is taken. As illustrated in the diagram, block **1818** comprising data "D" is modified after the snapshot was taken (in FIG. **18**B), and therefore a new block **1824** containing data "D_{prime}" is allocated for the active file system **1830**. Thus, the active file system **1830** comprises blocks **1812–1816** and **1820–1824** but does not contain block **1818** containing data "D". However, block **1818** containing data "D" is not overwritten because the WAFL system does not overwrite blocks on disk. The block **1818** is protected against being overwritten by a snapshot bit that is set in the blkmap entry for block **1818**. Therefore, the snapshot **1822** still points to the unmodified block **1818** as well as blocks **1812–1816** and **1820**. The present invention, as illustrated in FIGS. **18**A–**18**C, is unlike prior art systems that create "clones" of a file system where a clone is a copy of all the blocks of an inode file on disk. Thus, the entire contents of the prior art inode files are duplicated requiring large amounts (MB) of disk space as well as requiring substantial time for disk I/O operations.

As the active file system **1830** is modified in FIG. **18**C, it uses more disk space because the file system comprising blocks **1812–1820** is not overwritten. In FIG. **18**C, block **1818** is illustrated as a direct block. However, in an actual file system, block **1818** may be pointed to by indirect blocks as well. Thus, when block **1818** is modified and stored in a new disk location as block **1824**, the corresponding direct and indirect blocks are also copied and assigned to the active file system **1830**.

FIG. **19** is a diagram illustrating the changes that occur in block **1824** of FIG. **18**C. Block **1824** of FIG. **18**C is represented within dotted line **1824** in FIG. **19**. FIG. **19** illustrates several levels of indirection for block **1824** of FIG. **18**C. The new block **1910** that is written to disk in FIG. **18**C is labeled **1910** in FIG. **19**. Because block **1824** comprises a data block **1910** containing modified data that is referenced by double indirection, two other blocks **1918** and **1926** are also modified. The pointer **1924** of single-indirect block **1918** references new block **1910**, therefore block **1918** must also be written to disk in a new location. Similarly, pointer **1928** of indirect block **1926** is modified because it points to block **1918**. Therefore, as shown in FIG. **19**, modifying a data block **1910** can cause several indirect blocks **1918** and **1926** to be modified as well. This requires blocks **1918** and **1926** to be written to disk in a new location as well.

Because the direct and indirect blocks **1910**, **1918** and **1926** of data block **1824** of FIG. **18**C have changed and been written to a new location, the inode in the inode file is written to a new block. The modified block of the inode file is allocated a new block on disk since data cannot be overwritten.

As shown in FIG. **19**, block **1910** is pointed to by indirect blocks **1926** and **1918**, respectively. Thus when block **1910** is modified and stored in a new disk location, the corresponding direct and indirect blocks are also copied and assigned to the active file system. Thus, a number of data structures must be updated. Changing direct block **1910** and indirection blocks **1918** and **1926** causes the blkmap file to be modified.

The key data structures for snapshots are the blkmap entries where each entry has multiple bits for a snapshot. This enables a plurality of snapshots to be created. A snapshot is a picture of a tree of blocks that is the file system (**1830** of FIG. **18**). As long as new data is not written onto blocks of the snapshot, the file system represented by the snapshot is not changed. A snapshot is similar to a consistency point.

The file system of the present invention is completely consistent as of the last time the fsinfo blocks **1810** and **1870** were written. Therefore, if power is interrupted to the system, upon restart the file system **1830** comes up in a consistent state. Because 8–32 MB of disk space are used in typical prior art "clone" of a 1 GB file system, clones are not conducive to consistency points or snapshots as is the present invention.

Referring to FIG. **22**, two previous snapshots **2110**A and **2110**B exist on disk. At the instant when a third snapshot is created, the root inode pointing to the active file system is copied into the inode entry **2110**C for the third snapshot in the inode file **2110**. At the same time in the consistency point that goes through, a flag indicates that snapshot **3** has been created. The entire file system is processed by checking if BIT**0** for each entry in the blkmap file is set (**1**) or cleared (**0**). All the BIT**0** values for each blkmap entry are copied into the plane for snapshot three. When completed, every active block **2110–2116** and **1207** in the file system is in the snapshot at the instant it is taken.

Blocks that have existed on disk continuously for a given length of time are also present in corresponding snapshots **2110**A–**2110**B preceding the third snapshot **2110**C. If a block has been in the file system for a long enough period of time, it is present in all the snapshots. Block **1207** is such a block. As shown in FIG. **22**, block **1207** is referenced by inode **2210**G of the active inode file, and indirectly by snapshots **1**, **2** and **3**.

The sequential order of snapshots does not necessarily represent a chronological sequence of file system copies. Each individual snapshot in a file system can be deleted at any given time, thereby making an entry available for subsequent use. When BIT**0** of a blkmap entry that references the active file system is cleared (indicating the block has been deleted from the active file system), the block cannot be reused if any of the snapshot reference bits are set. This is because the block is part of a snapshot that is still in use. A block can only be reused when all the bits in the blkmap entry are set to zero.

Algorithm for Generating a Snapshot

Creating a snapshot is almost exactly like creating a regular consistency point as shown in FIG. **5**. In step **510**, all dirty inodes are marked as being in the consistency point. In step **520**, all regular files are flushed to disk. In step **530**,

special files (i.e., the inode file and the blkmap file) are flushed to disk. In step **540**, the fsinfo blocks are flushed to disk. In step **550**, all inodes that were not in the consistency point are processed. FIG. **5** is described above in detail. In fact, creating a snapshot is done as part of creating a consistency point. The primary difference between creating a snapshot and a consistency point is that all entries of the blkmap file have the active FS-bit copied into the snapshot bit. The snapshot bit represents the corresponding snapshot in order to protect the blocks in the snapshot from being overwritten. The creation and deletion of a snapshot is performed in step **530** because that is the only point where the file system is completely self-consistent and about to go to disk.

Different steps are performed in step **530** then illustrated in FIG. **6** for a consistency point when a new snapshot is created. The steps are very similar to those for a regular consistency point. FIG. **7** is a flow diagram illustrating the steps that step **530** comprises for creating a snapshot. As described above, step **530** allocates disk space for the blkmap file and the inode file and copies the active FS-bit into the snapshot bit that represents the corresponding snapshot in order to protect the blocks in the snapshot from being overwritten.

In step **710**, the inodes of the blkmap file and the snapshot being created are pre-flushed to disk. In addition to flushing the inode of the blkmap file to a block of the inode file (as in step **610** of FIG. **6** for a consistency point), the inode of the snapshot being created is also flushed to a block of the inode file. This ensures that the block of the inode file containing the inode of the snapshot is dirty.

In step **720**, every block in the blkmap file is dirtied. In step **760** (described below), all entries in the blkmap file are updated instead of just the entries in dirty blocks. Thus, all blocks of the blkmap file must be marked dirty here to ensure that step **730** write-allocates disk space for them.

In step **730**, disk space is allocated for all dirty blocks in the inode and blkmap files. The dirty blocks include the block in the inode file containing the inode of the blkmap file, which is dirty, and the block containing the inode for the new snapshot.

In step **740**, the contents of the root inode for the file system are copied into the inode of the snapshot in the inode file. At this time, every block that is part of the new consistency point and that will be written to disk has disk space allocated for it. Thus, duplicating the root inode in the snapshot inode effectively copies the entire active file system. The actual blocks that will be in the snapshot are the same blocks of the active file system.

In step **750**, the inodes of the blkmap file and the snapshot are copied to into the inode file.

In step **760**, entries in the blkmap file are updated. In addition to copying the active FS-bit to the CP-bit for the entries, the active FS-bit is also copied to the snapshot bit corresponding to the new snapshot.

In step **770**, all dirty blocks in the blkmap and inode files are written to disk.

Finally, at some time, snapshots themselves are removed from the file system in step **760**. A snapshot is removed from the file system by clearing its snapshot inode entry in the inode file of the active file system and clearing each bit corresponding to the snapshot number in every entry in the blkmap file. A count is performed also of each bit for the snapshot in all the blkmap entries that are cleared from a set value, thereby providing a count of the blocks that are freed (corresponding amount of disk space that is freed) by deleting the snapshot. The system decides which snapshot to delete on the basis of the oldest snapshots. Users can also choose to delete specified snapshots manually.

The present invention limits the total number of snapshots and keeps a blkmap file that has entries with multiple bits for tracking the snapshots instead of using pointers having a COW bit as in Episode. An unused block has all zeroes for the bits in its blkmap file entry. Over time, the BIT**0** for the active file system is usually turned on at some instant. Setting BIT**0** identifies the corresponding block as allocated in the active file system. As indicated above, all snapshot bits are initially set to zero. If the active file bit is cleared before any snapshot bits are set, the block is not present in any snapshot stored on disk. Therefore, the block is immediately available for reallocation and cannot be recovered subsequently from a snapshot.

Generation of a Snapshot

As described previously, a snapshot is very similar to a consistency point. Therefore, generation of a snapshot is described with reference to the differences between it and the generation of a consistency point shown in FIGS. **17**A–**17**L. FIGS. **21**A–**21**F illustrate the differences for generating a snapshot.

FIGS. **17**A–**17**D illustrate the state of the WAFL file system when a snapshot is begun. All dirty inodes are marked as being in the consistency point in step **510** and regular files are flushed to disk in step **520**. Thus, initial processing of a snapshot is identical to that for a consistency point. Processing for a snapshot differs in step **530** from that for a consistency point. The following describes processing of a snapshot according to FIG. **7**.

The following description is for a second snapshot of the WAFL file system. A first snapshot is recorded in the blkmap entries of FIG. **17**C. As indicated in entries **2324**A–**2324**M, blocks **2304**–**2306**, **2310**–**2320**, and **2324** are contained in the first snapshot. All other snapshot bits (BIT1–BIT**20**) are assumed to have values of 0 indicating that a corresponding snapshot does not exist on disk. FIG. **21**A illustrates the file system after steps **510** and **520** are completed.

In step **710**, inodes **2308**C and **2308**D of snapshot **2** and blkmap file **2344** are pre-flushed to disk. This ensures that the block of the inode file that is going to contain the snapshot **2** inode is dirty. In FIG. **21**B, inodes **2308**C and **2308**D are pre-flushed for blkmap file **2344** and snapshot **2**. Buffer **2308** is already marked with an asterisk because inodes **2308**A and **2308**B are dirty in FIG. **21**A.

In step **720**, the entire blkmap file **2344** is dirtied as illustrated in FIG. **21**B, where block **2326** is marked with an asterisk. This will cause the entire blkmap file **2344** to be allocated disk space in step **730**. In step **730**, disk space is allocated for dirty blocks **2308** and **2326** for inode file **2346** and blkmap file **2344** as shown in FIG. **21**C. This is indicated by a double asterisk (**) beside blocks **2308** and **2326**. This is different from generating a consistency point where disk space is allocated only for blocks having entries that have changed in the blkmap file **2344** in step **620** of FIG. **6**. Blkmap file **2344** of FIG. **21**C comprises a single block **2324**. However, when blkmap file **2344** comprises more than one block, disk space is allocated for all the blocks in step **730**.

In step **740**, the root inode for the new file system is copied into inode **2308**D for snapshot **2**. In step **750**, the inodes **2308**C and **2308**D of blkmap file **2344** and snapshot **2** are flushed to the inode file as illustrated in FIG. **21**D. The diagram illustrates that snapshot **2** inode **2308**D references blocks **2304** and **2308** but not block **2306**.

In step **760**, entries **2326**A–**2326**L in block **2326** of the blkmap file **2344** are updated as illustrated in FIG. **21**E. The diagram illustrates that the snapshot 2 bit (BIT**2**) is updated as well as the FS-BIT and CP-BIT for each entry **2326**A–**2326**L. Thus, blocks **2304**, **2308–2312**, **2316–2318**, **2322**, and **2326** are contained in snapshot **2** whereas blocks **2306**, **2314**, **2320**, and **2324** are not. In step **770**, the dirty blocks **2308** and **2326** are written to disk, as indicated in FIG. **21**F.

Further processing of snapshot **2** is identical to that for generation of a consistency point illustrated in FIG. **5**. In step **540**, the two fsinfo blocks are flushed to disk. Thus, FIG. **21**F represents the WAFL file system in a consistent state after this step. Files **2340**, **2342**, **2344**, and **2346** of the consistent file system, after step **540** is completed, are indicated within dotted lines in FIG. **21**F. In step **550**, the consistency point is completed by processing inodes that were not in the consistency point.

Access Time Overwrites

Unix file systems must maintain an "access time" (atime) in each inode. Atime indicates the last time that the file was read. It is updated every time the file is accessed. Consequently, when a file is read the block that contains the inode in the inode file is rewritten to update the inode. This could be disadvantageous for creating snapshots because, as a consequence, reading a file could potentially use up disk space. Further, reading all the files in the file system could cause the entire inode file to be duplicated. The present invention solves this problem.

Because of atime, a read could potentially consume disk space since modifying an inode causes a new block for the inode file to be written on disk. Further, a read operation could potentially fail if a file system is full which is an abnormal condition for a file system to have occur.

In general, data on disk is not overwritten in the WAFL file system so as to protect data stored on disk. The only exception to this rule is atime overwrites for an inode as illustrated in FIGS. **23**A–**23**B. When an "atime overwrites" occurs, the only data that is modified in a block of the inode file is the atime of one or more of the inodes it contains and the block is rewritten in the same location. This is the only exception in the WAFL system; otherwise new data is always written to new disk locations.

In FIG. **23**A, the atimes **2423** and **2433** of an inode **2422** in an old WAFL inode file block **2420** and the snapshot inode **2432** that references block **2420** are illustrated. Inode **2422** of block **2420** references direct block **2410**. The atime **2423** of inode **2422** is "4/30 9:15 PM" whereas the atime **2433** of snapshot inode **2432** is "5/1 10:00 AM". FIG. **23**A illustrates the file system before direct buffer **2410** is accessed.

FIG. **23**B illustrates the inode **2422** of direct block **2410** after direct block **2410** has been accessed. As shown in the diagram, the access time **2423** of inode **2422** is overwritten with the access time at which direct block **2410** was accessed. Thus, the access time **2423** of inode **2422** for direct block **2410** is "5/1 11:23 AM".

Allowing inode file blocks to be overwritten with new atimes produces a slight inconsistency in the snapshot. The atime of a file in a snapshot can actually be later than the time that the snapshot was created. In order to prevent users from detecting this inconsistency, WAFL adjusts the atime of all files in a snapshot to the time when the snapshot was actually created instead of the time a file was last accessed. This snapshot time is stored in the inode that describes the snapshot as a whole. Thus, when accessed via the snapshot, the access time **2423** for inode **2422** is always reported as "5/1 10:00AM". This occurs both before the update when it may be expected to be "4/30 9:15PM", and after the update when it may be expected to be "5/1 11:23AM". When accessed through the active file system, the times are reported as "4/30 9:15PM" and "5/1 11:23AM" before and after the update, respectively.

In this manner, a method is disclosed for maintaining a file system in a consistent state and for creating read-only copies of the file system.

We claim:

1. A method for recording a plurality of data about a plurality of blocks of data stored in storage means comprising the steps of:

maintaining a means for recording multiple usage bits per block of said storage means, wherein one bit of said multiple bits per block for each of said blocks indicates a block's membership in an active file system and one or more bits indicated membership in one or more read-only copies of a file system; and

storing in said means for recording multiple usage bits per block multiple bits for each of a plurality of said blocks of said storage means.

2. A method for maintaining a file system stored in non-volatile storage means at successive consistency points said file system comprising blocks of data, said blocks of data comprising blocks of regular file data and blocks of meta-data file data referencing said blocks of data of said file system, said meta file data comprising a file system information structure comprising data describing said file system at a first consistency point said computer system further comprising memory means, said method comprising the steps of:

maintaining a plurality of modified blocks of regular file data and meta-data file data in said memory means, said modified blocks of data comprising blocks of data modified from said first consistency point;

designating as dirty blocks of meta-data file data referencing said modified blocks of regular file data and meta-data file data, said dirty blocks of meta-data file data comprising blocks of meta-data file data to be included in a second consistency point;

copying said modified blocks of regular file data referenced by said dirty blocks of meta-data file data to free blocks of said non-volatile storage means;

copying blocks comprising said modified blocks of meta-data file data referenced by said dirty blocks of meta-data file data to free blocks of said non-volatile storage means;

modifying a copy of said file system information structure maintained in said memory means to reference said dirty blocks of meta-data file data:

copying said modified file system information structure to said non-volatile storage means.

3. The method of claim **2** wherein said blocks of meta-file data comprise one or more blocks of inode file data and one or more blocks of blockmap file data and wherein said step of copying said modified blocks of meta-data file data to free blocks of said non-volatile storage means further comprises the steps of:

copying an inode referencing one or more blocks of blockmap file data to a block of inode file data maintained in said memory means;

allocating free blocks of said non-volatile storage means for said block of inode file data and one or more modified blocks of blockmap file data:

updating said inode referencing said one or more blocks of blockmap file data to reference said one or more free blocks of said non-volatile storage means allocated to said one or more modified blocks of blockmap file data;

copying said updated inode to said block of inode file data;

updating said one or more blocks of blockmap file data;

writing said updated one or more blocks of blockmap file data and said block of inode file data to said allocated free blocks of said non-volatile storage means.

4. A method for maintaining a file system comprising blocks of data stored in blocks of a non-volatile storage means at successive consistency points comprising the steps of:

storing a first file system information structure for a first consistency point in said non-volatile storage means, said first file system information structure comprising data describing a layout of said file system at said first consistency point of said file system;

writing blocks of data of said file system that have been modified from said first consistency point as of the commencement of a second consistency point to free blocks of said non-volatile storage means;

storing in said non-volatile storage means a second file system information structure for said second consistency point, said second file system information structure comprising data describing a layout said file system at said second consistency point of said file system.

5. The method of claim **4** wherein said step of storing said first file system information structure in said non-volatile storage means comprises the step of:

storing first and second copies of said first file system information structure at first and second locations respectively of said non-volatile storage means;

and wherein said step of storing said second file system information structure in said non-volatile storage means comprises the steps of:

overwriting said first copy of said first file system information structure with a first copy of said second file system information structure; and

overwriting said second copy of said first file system information structure with a second copy of said second file system information structure.

6. The method of claim **5** wherein said first and second locations of said non-volatile storage means comprise fixed predetermined locations of said non-volatile storage means.

7. The method of claim **5** wherein each copy of said file system information structure comprises means for determining a most recent version of said file system information structure and means for determining validity of said file system information structure, further comprising the steps of:

after a system failure, reading said first and second copies of said file system information structure from said first and second locations of said non-volatile storage means;

determining a most recent valid file system information structure from said first and second copies of said file system information structure.

8. A method for creating a plurality of read-only copies of a file system stored in blocks of a non-volatile storage means, said file system comprising meta-data identifying blocks of said non-volatile storage means used by said file system, comprising the steps of:

storing meta-data for successive states of said file system in said non-volatile storage means;

making a copy of said meta-data at each of a plurality of said states of said file system;

for each of said copies of said meta-data at a respective state of said file system, marking said blocks of said non-volatile storage means identified in said meta-data as comprising a respective read-only copy of said file system.

9. The method of claim **8** wherein said step of marking said blocks comprising a respective read-only copy of said file system comprises placing an appropriate entry in a means for recording multiple usage bits per block of said non-volatile storage means.

10. The method of claim **9** wherein said means for recording multiple usage bits per block of said non-volatile storage means comprises a blockmap comprising multiple bit entries for each block.

11. The method of claim **8** wherein said meta-data comprises pointers to a hierarchical tree of blocks comprising said file system.

12. The method of claim **8** wherein said meta-data comprises structures representing files of said file system.

13. The method of claim **12** wherein said structures representing files of said file system comprise inodes.

14. The method of claim **8** further comprising the step of:

preventing overwriting of said blocks marked as belonging to a read-only copy of said file system.

15. The method of claim **8** comprising the step of unmarking said blocks marked as belonging to a read only copy of said file system when said read only copy of said file system is no longer needed.

16. The method of claim **8** wherein a plurality of said blocks marked as belonging to a read-only copy of said file system comprise data ancillary to said file system, said method further including the steps of:

allowing said ancillary data to be overwritten; and

otherwise preventing overwriting of said blocks marked as comprising a read only copy of said file system.

17. The method of claim **16** wherein said ancillary data comprises access time data.

18. The method of claim **8** wherein said meta-data comprises a root structure referencing structures representing files of said file system, and wherein said copies of said meta-data comprise copies of said root structure.

19. The method of claim **18** wherein said root structure comprises a root inode.

20. The method of claim **8** further comprising the step of using one or more of said read-only copies of said file system to back-up said blocks comprising one or more consistency points of said file system.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO : 5, 819, 292

DATED : October 6, 1998

INVENTOR(S) : David Hitz, Michael Malcolm, James Lau, Byron Rakitzis

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the claims, on page 24, replace claim 1 with the following:

1. A method for recording a plurality of data about a plurality of blocks of data stored in storage means comprising the steps of:

maintaining a means for recording multiple usage bits per block of said storage means;

storing, in said means for recording multiple usage bits per block, multiple bits for each of said plurality of said blocks of said storage means; and

reusing at least one of said plurality of blocks of data in response to at least one of said multiple usage bits.

Signed and Sealed this

Fourteenth Day of March, 2000

Attest:

Q. TODD DICKINSON

Attesting Officer

Commissioner of Patents and Trademarks